Power Quality Analysis and Haromic Treatment

Piaopiao You

North China University of Water Resources and Electric Power, Zhengzhou 450046, Henan, China

Abstract

As a large amount of novel power electronic equipment floods into power grid, harmonic has become a unignorable factor that leads to the deterioration of power quality. This study first briefly introduced main characteristics of harmonic as well as its damages and pollutions to power system and signal. Parallel hybrid active power filter (PHAPF) proved to be an effective device that can not only suppress harmonic dynamically but also compensate certain reactive power, which has gradually become the research emphasis. Then, the composition and principle of PHAPF were introduced in detail, and harmonic detection circuits and compensation current generators were compared and analyzed respectively. Results reveal that, among the existing harmonic detection methods, dq-transformation-based method can eliminate the effects of voltage harmonic and asysmterical voltage and effectively solve the phase problem in analog filter, and cannot increase or decrease some frequency components. Accordingly, dq-transformation-based harmonic detection method shows great advantages and potential. Among all tracking control methods of compensating current, hysteresis control method exhibits favorable real-time and adapative performances and more suitable for extensive applications and popularization.

Keywords

power quality; power filter; harmonic detection; tracking control of compensation current; hysteresis control

1. Introduction

As a unique commodity, electric power plays an increasingly important role in human’s production and daily life. Meanwhile, obvious contradictions arose in electric power development. On the one hand, for addressing the problems in the development of power system, various new devices and new technologies such as new rectifiers, electrified railway equipment and reactive power compensation equipment appeared constantly; on the other hand, these new devices are featured by nonlinearity, impact and imbalance, which would inject electromagnetic interference such as high-order harmonics into the power system during the operation process, thereby inducing voltage fluctuation, flickering, three-phase imhance and other power quality problems. Poor-quality power can trigger large-area power blackout, affect the normal operations of the whole system and some electric equipment, and even cause the failure of protetive equipment, which would pose a great threat to the safety of the whole power system. According to the statistics, losses due to power quality reach up to approximately 50 billion dollars in the USA. Conclusively, power quality has aroused extensive attension from international schoalrs. China has gradually realized the importance of power quality while strengthening the efforts to the development of infrastructures in the power grid.

In the late1970s, various power converters have been widespread with the development of power electronics and the related techniques, and the international academic circles have paid much attention to the question wheter the existing power system can sustain the harm of harmonics. Some countries and famous international organizations (for example, the International Electrotechnical Commission (IEC)), have formulated various harmonic standards for power distribution systems, power equipment and consumers as well as household appliances. China has been investigating harmonic pollution treatment for many years and has gained a lot of favorable results in addressing harmonic pollution in regional and electrified railway equipment.

2. Classification and research status of power quality problems

Power quality mainly includes voltage quality, current quality, power supply quality and power utilization quality. Qualified power quality can provide electric energy for electric equipment and satisfy the equipment's power utilization requirements, while causing no equipment failures or malfunctions. Contrarily, poor power quality would be deteriorated if a series of quality-related questions cannot be effectively controlled.

2.1 Classification of power quality problems

In terms of emergence and duration time, power quality problems can be divided into steady power problems and transient power problems [1~2].

2.1.1 Steady power problems

Steady power problems are mainly featured by waveform distortion, during which voltage variation lasts over 1 min. Steady power problems can be further into the following types of problems.

(a) Overvoltage, i.e., voltage fluctuates over 1 min and exceeds the nominal voltage. Overvoltage is generally related to load switching.

(b) Undervoltage, i.e., voltage fluctuates over 1 min but the value is smaller than the nominal voltage. On the contrary, undervoltage may be induced by the connection of a certain load or the disconnection of a certain capacitor bank.

(c) Voltage imbalance, i.e., the ratio of the maximum voltage deviation to the average three-phase voltage exceeds the specified standard. The primary cause is load imbanlance or the fusing of a fuse at a certain phase in the three-phase capacitor bank.

(d) Waveform distortion, i.e., voltage or current waveform deviates from the sinusoidal waveform at the steady working frequency, which is generally caused by the nonlinear devices in the power system. Harnomic under waveform distortion conditions can deteriorate the power quality indexes; specifically, on the one hand, harmomic resonace in the power network can be triggered, thereby leading to the interruption of normal power supply, the expansion of power outrage, network splitting and other accidents; on the other hand, it may endanger the performances of some devices such as motor, transformer, switch, protector and automatic control devices in dealing with some problems main including heating, vibration noise, insulation and zero crossing point (ZCP)

Conclusively, when the steady power quality indexes drop, a series of accidents would be induced; moreover, the further development of accidents will bring about unpredictable influences on the system's stability. Harmonic and three-phase imbanlance are the most important steady power quality index.

2.1.2 Dynamic power system problems

With the rapid development of power market, dynamic power problems have gained more and more attention rather than been neglected. Dynamic power quality problems are featured by tranistent duration and include the following several types.

(a) Short power supply interruption, which refers to the interruption lasting from half a cycle to 3 s. This may be caused by system failure, electric equipment failure, control malfunction or three-phase voltage imbalance.

(b) Transient voltage drop or increase, which refers to voltage variation phenomenon lasting from half a cycle to 1 min, or increase or decrease of effective voltage to 110%~180% or 10%~90% of the nominal voltage. In most cases, transient voltage drop or increase can be attributed to system failure.

(c) Voltage transient, which refers to the rapid voltage change at a short time.

(d) Voltage flicker, which refers to the regular variation of the voltage waveform envelope or a series of random variations of voltage amplitude. This may be caused by flashover or circuit-toground discharge.

As shown in Fig. 1, voltage drop always appears in dynamic electric power quality problems

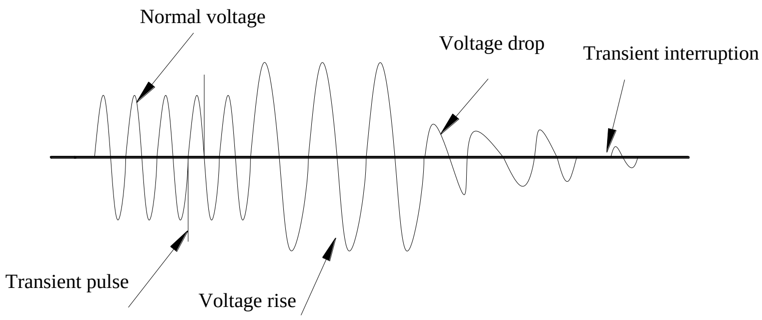

Fig. 1 Illustration of various dynamic electric power quality patterns

Normal voltage/Transient pulse/Voltage rise/Voltage drop/Transient interruption

2.2 Research status of power quality problems

Deterioration of power quality and the related pollutions are mainly sourced from users, which would severely affect the power system after the propagation and diffusion via the power transmission and supply links. As large-scale wind power generation, solarenergy power grid connection and distribution power generation appeared and developed, power quality problems exhibit some new characteristics, and power generation link also becomes a negligible pollution source and needs real-time monitor and control.

Many big power companies in foreign countries all actively advocate the monitor and control of powe quality, and also established some open power quality networks for releasing power quality information in real time. In China, power supply voltage deviation, grid harmonic, frequency deviation in the power system, three-phase voltage imbalance, transient overgvoltage, instantaneous overvoltage, voltage fluctuation and voltage flicker are common used in monitor and evaluation of power quality. Aiming at improving power quality, several universities and research institutes have conducted a great deal of research on the development of power compensation devices mainly including active power filter (APF), dynamic var compensator (SVC) and power quality comprehensive compensation devices. Hybrid active power filter (HAPF), which combines both active and reactive power, can be connected to the power system in parallel during the operation. Owing to its several advantages such as simple connection, excellent performance, stable operation and the operation in combination with the traditional passive compensation devices, HAPF is particularly suitable for the power development in China for achieving the suppression of dynamic harmonics and high-capacity reactive compensation. Gaining in-dpeth knowledge of the performance of HAPF has profound significance to improving electric power quality.

3. Power harmonic

As a large amount of novel power electronic equipment swarms into the power grid, harmonic has become a negligible factor that deteriorates power quality. According to an internationall recoganized definition, harmonic refers to the component of sinusoidal wave of the electronic quanity in a cycle, whose frequency is intergral multiple of fundamental frequency. Harmonic is essentially a kind of waveform distortion and induced by nonlinear devices in the power system. As to the nonlinear devices, the flowing current and the applied voltage are disproportionate, i.e., Ohm’s Law is inapplicable [2, 3]. As shown in Fig. 2, even if ideal sinusoidal voltage is applied, the current outflowing from the nonlinear resistance is nonsinusoidal.

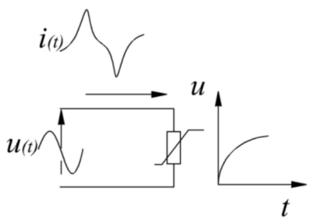

Fig. 2 Current distortion induced by nonlinear resistance

Harmonic sources are a kind of electric equipment generating harmonic in the system, which are also characterized by nonlinearity. Harmonic can cause signal interference and thus pollute and do harms to power system. Pollutions and damages mainly include the following aspects.

The damages to power system mainly include: (1) causing additional harmonic loss and heating of the rotational motor and shortening the service life; (2) triggering harmonic and overvoltage and resulting in the failure and breakdown of electrical components and devices; (3) leading to the error of power measurement.

In terms of signal interference, harmonic's adverse effects mainly include: (1) generating electromagnetic interference in the communication system and deteroritating the comminunication quality; (2) causing the misoperation of some important and sensitive automatic control and protective equipment; (3) endangering the power programmer's normal operation.

Power quality degradation induced by the electrical railway load is becoming increasingly serious. Cai *et al*. monitored the power quality at around Yingtan South Electrical Railway Station and compared the monitoring data with the national standard; through analysis, they finally ound that the electrical railway load was a harmonic pollution source, and the overall harmonic distortion rate was far beyond the standard; even seriously, the total distortion rate of voltage harmonic exceeded the standard in over 51.11% of the operating time [4]. Therefore, this station should pay much attention to the control of harmonic source. Electric-arc furnace is experiencing rapid development in steel-making industry, which is also a kind of typical harmonic source. Wei *et al*. analyzed the monitored power data at around a steel plant, and found that the harmonic and flickering generated from this steel plant exceeded the standard and deteriorated the power quality; moreover, they concluded that harmonic and flickering were very likely the dominant factor that led to the burnout of generator excitation in the power station [5]. This is also a typical of user-caused power quality degradation, and therefore, harmonic should be effectively treated for ensuring that thee power indexes were within the controllable range.

As described above, harmonic problems are common in the system's operation process and show great potential to deteriorate power quality. Accordingly, it is urgently necessary to treat harmonic pollutions. The research on power quality is just at a starting stage in China, and lags far behind the foreign advanced level; however, Chinese scholars have gain certain useful results in theory.

Power harmonic can generally be suppressed or alleviated by two different kinds of measures, namely, preventive measures and compensatory measures. Using preventive measures, the devices connecting to power grid are updated for limiting or preventing from the generation of harmonic components. To be specific, the harmonic generation can be reduced in the design of electrical equipment, manufacturing and layout, or the harmonic of the rectifier can be limited by increasing the pulse number or adopting controllable rectification. Compensatory measures mainly refer to harmonic inhibition by adding the devices at around the harmonic source, which are mainly implemented by varying feeder parameters or using filter. Preventive measures alwalys have high cost and low effiency; moreover, high-order harmonic would be generated when the rectifier uses pulse width modulation (PWM) technique. Therefore, for better addressing harmonic problems, we should start from the harmonic source and prevent the harmonic current from flowing to the power grid at around the harmonic source, which is also extensively used in power system for harmonic suppression.

4. Parallel hybrid active power filter (PHAPF)

In orer to improve power quality and effectively monitor and control harmonic, the harmonic source users should adopt filtering measures or dynamic reactive compensation and determine the compensation rate of the power grid. In particular, since the voltage distortion rates are extremely high in some regions in power distribution network, the user-side reactive power compensation device in the power grid should be designed as the system with comprehensive functions that can compensate both harmonic and reactive power so as to reduce the overall distortion rate of voltage harmonic.

Using Fourier transform, any periodic distorted harmonic waveforms can be expressed by the sum of sinusoidal waveforms and show three-phase symmetry. HAPF, which combines APF and PF in parallel, is suitable for harmonic loads with both three-phase symmetry and asymmetry for compensation.

High-power power electronic devices are always expensive. Traditional LC filter can only filter out the harmonics at a fixed frequency, whose filter performances are sensitive to the system's operation mode, grid impedance and frequency; in additoinaly, LC filter is easily connected to the system and the source impedance in series and parallel, respectively. By constrast, APF, as s kind of novel power electronic devices for compensating reactive power, can provide dynamic compensation for the harmonics and reactive power generated by nonlinear loads; however, APF requires high initial investment and subsequent operation and is poor in practicability. Accordingly, Qu *et al.* adopted the parallel hybrid APF (PHAPF) with a small active capacity; this device includes the advantages of APF and can effectively compensate three-phase symmetrical harmonic load [6].

4.1 Compositions and principle of PHAPF

Fig. 3 illustrates the composition of PHAPF, in which the harmonic source served as the load for generating harmonic and consuming reactive power, PF denotes the passive filter such as LC filter and can eliminate high-order harmonics, APF includes harmonic detection circuit, current tracker, drive circuit and main circuit and mianly used for compensating reactive power and improving the whole system's compensation performances.

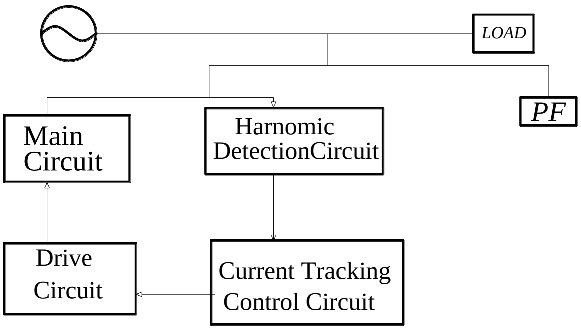

Fig. 3 Illustration of the composition of the parallel hybrid APF

A parallel APF mainly consists of two parts—harmonic detection circuit and compensation current generating device. The former is responsible for the detection of some current components in the compensate object such as harmonic and reactive power, while the latter is composed of current tracking control circuit, drive circuit and main circuit and used for generating compensation current according to the command signal of signal compensation. This command signal is sent by the harmonic detection circuit and then magnified by the compensating current generating device. Afterwards, the compensating current can be offset by the harmonic and reactive power in the load to be compensated, finally yielding expected current and voltage. PHAPF exhibits the following characteristics: (a) small capacity since PF is responsibe for most of harmonics; (b) can realize a large capacity of load compensation by a small capacity of APF; (c) low cost and strong practicality.

4.2 Harmonic detection method based on dq transformation

For an APF, the filtering performances heavily depend on the detection of harmonics and fundamental reactive current. Traditional real-time harmonic detection can be realized in the following two ways. In the first method, scholars conduct Fourier transform on the load current with harmonic components, then add various-order harmonic currents together and finally acquire the total harmonic current component. In the second method, the required harmonic current in the load current is filtered out via a filter. Currently, harmonic in power system can be detected by the following four methods, namely, harmonic detection using an analog filter, harmonic detection method based on instantaneous reactive power theory, harmonic detection method based on fast Fourier transform and harmonic detection method based on wavelet analysis. Table 1 lists the advantages and disavantages of these methods in detail.

Table 1 Comparison among four harmonic current detection methods

Advantages and disadvantages / Detection methods	Advantages	Disadvantages
Harmonic detection using an analog filter	Simple principle and circuit structure, low cost and the capability of filtering out the harmonics at a fixed frequency	Large error, poor real-time performance and great sensitivity to circuit parameters.
Harmonic detection method based on instantaneous reactive power theory	Being applicable to the detection of high-order harmonics and fundamental reactive current in three-phase current under three-phase voltage symmetry conditions, favorable real-time performance, short delay time and the capability of detecting harmonics and compensating reactive power	Including many hardwares and high cost
Harmonic detection method based on fast Fourier transform	Simple implementation, fast computation, high precision, multiple functions and convenience in use	This method can detect the resolution of various-order harmonic components, and generate spectrum aliasing, spectrum leakage and barrage effect.
Harmonic detection method based on wavelet analysis	Being applicable to the analysis and processing of abrupt signals and favorable real-time performances	High technical requirements and less application

Additionally, harmonic detection method based on dq transformation is a novel harmonic detection method with great potential. By constrast with the detection based on instantaneous reactive power theory, dq-transformation-based harmonic detection method can eliminate the effects of voltage harmnics and asymmetrical voltage and address the phase problems in using analog filter, while not increasing or decreasing some frequency components.

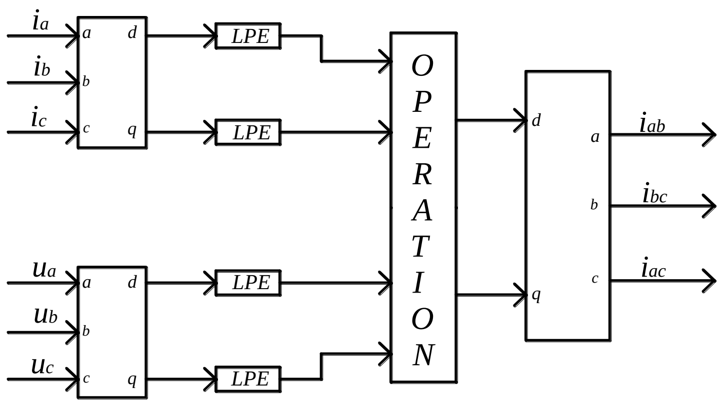

Fig. 4 Harmonic detection circuit based on dq transformation

DQ transformation, also referred to as Park transformation, is a kind of famous transformation of reference coordinates from the stator side of the rotary motor to the rotor side. Fig. 4 shows the harmonic detection circuit based on dq transformation. In 1929, Park first proposed to describe the fundamental equation of the synchronous motor in dq0 coordinate system. After half a century of development, the application of dq transformation has been expanded to many technical fields such as power quality analysis. The transformations of three-phase AC voltage and dq coordinate can be written as:

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = C \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \quad (1)$$

$$C = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin \omega t & \sin(\omega t - 2\pi/3) & \sin(\omega t + 2\pi/3) \\ -\cos \omega t & -\cos(\omega t - 2\pi/3) & -\cos(\omega t + 2\pi/3) \end{bmatrix} \quad (2)$$

This method can detect the load harmonic current and reactive powr under both symmetrical and distorted conditions.

4.3 Control mode of PHAPF

As described in Section 4.2, APF includes the compensation current trackor, and the generated compensation current can change with the variation of command signal in real time. It set high demands on the real-time performance of the compensating current. On the other hand, the filtering performance of a PHAPF mainly depends on the selected control method and algorithm. Tracking-mode PWM control was employed for current control, which mainly includes voltage tracking control and current tracking control. Current tracking control can be further divided into triangular wave control, hysteresis control and periodic sampling control, among which the first two methods are most extensively used. There exist many voltage tracking control methods such as adaptive PWM control, error PWM control and spatial vector PWM control.

Cheng *et al.* described the principle and characteristics of triangular wave control and hysteresis control in detail in Ref. [7]. In practical applications, spatial vector PWM control now is being more and more used owing to its clear concept and principle. Compared with hysteresis control, spatial vector PWM at a lower switching frequency control can achieve more favorable performance. Table 2 lists the specific advantages and disadvantages of these three control methods.

Table 2 Comparison among three common tracking control methods of compensating current

Control method	Advantages	Disadvantages
Triangular wave control method	Simple control, good current response (being inferior to hysteresis control), fixed switching frequency	Great switching losses, generation of high-frequency distorted components, high-frequency signal distortion, slow progress, limited applications in high-power conditions
Hysteresis control method	Simple hardware circuit, favorable real-time performance, fast current response and strong adapativity to load	Unfixed switching frequency, easily producing overlarge pulsating current and switching noise, switching frequency, response speed and current precision are easily affected by the hysteresis width
Spatial vector PWM control method	High utilization ratio of DC voltage, high control precision, favorable dynamic responde and can reduce switching frequency	Great computation burden and complex algorithm

These three control methods all show advantages and disadvantages. It is hard to compare them and we should select an appropriate method in accordance with system requirements. In this study, hysteresis control was used. Fig. 5 illustrates the principle of the hysteresis comparion method of one-phase control. Using this method, the difference between i_c* and i_c, denoted as Δi_c, was adopted as the input of the hyteresis comparator, which then ouput PWM signal for controlling the switch on-off of the main circuit and thereby the variation of the compenstating current i_c. Asusming that H denote the hysteresis bandwidth, when Δi_c >H, the hyteresis comparator outputs 1 for achieving the control of the switch on-off of the converter in the PHAPF so as to reduce the compensation current; when Δi_c <-H, the hyteresis comparator outputs 0 for achieving the switch on-off of the converter in the PHAPF so as to increase the compensation current; when -H<Δi_c <H, the switch on-off of the converter in the PHAPF is controlled so that the compensation current remains unchanged. Accordingly, the precision of the compensation current of APF as well as switching frequency can be controlled by adjusting the value of H.

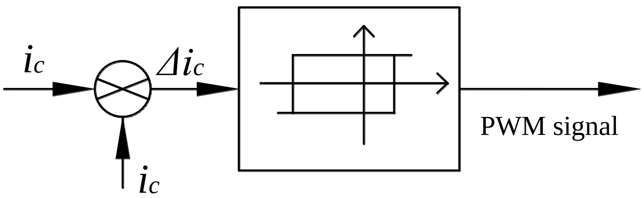

Fig. 5 Illustration of the principle of the hysteresis comparion method of one-phase control

If i_c is too large, the switching frequency of the converter may be too high under the fixed hysteresis bandwidth; when the switching frequency exceedes the device's maximum working frequency, the device may be burned down. Contrarily, since the hysteresis bandwidth is fixed, too small i_c may lead to too large relative tracking precision error of the compensation current. To settiling these disadvantages, two solutions were proposed, one is to adopt a new design scheme so that the hysteresis bandwidth of the hysteresis comparator (H) can be adjusted with the value of i_c, and the other way is to use the clock-controlled hysteresis comparator.

4.4 Practical application of PHAPF

Gu et al. assessed the power quality in Yancheng City,Jiangsu,China,and adopted dq transformation based harmonic detection method; according to their detection results, pollution was a common phenomenon for nonlinear big consumers in power system, mainly including low power factor as well as overlarge voltage and current distortion rate. After entering into the power distribution network through power transmission and distribution lines, harmonic current from these harmonic sources would pollute the whole power grid and become the main harmonic source in Yancheng. The simulation results with the use of PHAPF demonstrate that the fundamental reactive power can be completely eliminated and current distortion rate was also greatly reduced, which can provide great reference values for the treatment of harmonic pollutions in Yancheng.

5. Conclusion

With the enhancement of China’s economy, science and technology, various novel power electronic devices are becoming more widespread, causing significantly variation of load structure, and therefore, power quality of the power system has aroused much attention from enterprises and users. Power quality problems include steady power problems and transient power problems. The deterioration and pollution of power quality come from power supply enterprises and users, and therefore, the key to the improvement of power quality is to effectively and accurately detect and control power quality indexes. PHAPF can effectively inhibit harmonics and compensate reactive power. This study first analyzed the principle and composition of the PHAPF, investigated dq-transformatiom-based harmonic detection method in detail and examined hysteristic comparison control method and the compensation of harmonic current. The following conclusions were drawn.

(1) The harmonic detection method based on dq transformation shows great application values, and is applicable to three-phase three-wire power systems. Compared with the harmonic detection based on instantaneous reactive power theory, dq-transformation-based detection method can remove the effects of voltage harmonic and asymmetrical voltage as well as the phase problems in analog filter, and simultaneously will not increase or decrease some frequency components.

(2) Through in-dpeth analysis of hysteresis control method, it can be found that, using this method, the system performances are restricted by hysteresis bandwidth. Accodingly, some helpful suggestions for improving the defects were proposed.

(3) This study focused on the design of the detection and control of parallel APF, and the design of the parameters of main circuit will be the research emphasis in future research.

Chinese researchers have conducted a great deal of research on the detection and evaluation of power quality and acquired many useful results. With the rapid development of computer communication technology and network technique, power quality detection now is developing towards on-line monitoring and real-time analysis and becoming more networked and intelligent, and the comprehensive treatment of power quality management still needs further development. APF is generally recognized as the most effective solution of comprehensive harmonic pollution treatment. In addition to compensating harmonic current and reactive power, APF can also balance three-phase voltage and suppress voltage flicker. However, detection and control technique should have more favorable real-time performance and improved compensation performances, which sets higher requirements on detection and control methods. Some more simple and accurate methods should be developed and updated.

Acknowledgements

This paper is sponsored by Keynote Project of Scientific and Technology Research from the Department of Education in Henan Province (12A470005); Natural Science Funding Project from the Department of Education in Henan Province (2011A470005).

References

[1] Jiang Ping, Zhao Jianfeng, Tang Guoqing. Research of the Problems of Electric Power Quality and their Management Methods[J]. Jiangsu Electrical Engineering, 2003, 22(1):16-18.

[2] Xiao Xiangning. Analysis and Control of Power Quality[M]. China Electric Power Press, 2010.

[3] Liu Chengjun. Analysis Method of Power quality [M]. China Electric Power Press, 2011.

[4] Cai Heng, Chen Bin, Shi Huan. Analysis and Research of Power Quality of Yingnan Electric Railway[J]. Central China Electric Power, 2010, 23(1):10-13.

[5] Wei Caimeng. 35kV Duohua Line 315(steel mill) Power Quality Analysis [J]. Science Technology Enterprise, 2012(13):192-192.

[6] Qu yuchen. Harmonic on Power System Elimination Technologies[D]. Northeast Petroleum University, 2006.

[7] Cheng Lixia. A New Harmonic Current Detection Method and System Control of the Shunt Hybrid Active Power Fileter[D]. Jiangsu University, 2010.

[8] Song Qiang, Liu Wenhua. A New Space Vector Modulation Method Based on Reference Voltage Decomposition Formultilevel Vsi[J]. Power Automation System, 2002, 26(20):35-38.