Research on Synthesis Control of Power Quality for Electrified Railway

Xiangzheng Xu[1、2]
1 School of Electrical Engineering, Wuhan University, Wuhan , China
2 School of Electrical Engineering, East China Jiaotong University, Nanchang, China
Email: ecjtuxxz@sina.com

Baichao Chen
School of Electrical Engineering, Wuhan University, Wuhan , China
Email: xzxu@4y.com.cn

***Abstract*—This paper analyzes necessity of synthesis control of power quality aiming at characteristics of traction power supply system for electrified railway. According to the fact that the existing power quality control, the measure and means were introduced, analyzed and compared in detailed. From reliability, technology and economy point, the project of synthesis Control was put forward on power quality of electrified railway in the paper. In order to achieve real-time detection and compensation for power quality of electrified railway traction power system, this paper provides a detection method of selective harmonic current, so vertiginous harmonic current of traction load is detected. Synchronously vertiginous passive power is gained basing on hilbert digital phase-shifting filter. And imbalance load current is balanced through regulating magnetron static VAR compensator (SVC) device. The kind new injection-type hybrid active power filter (HAPF) combined with magnetron SVC make to compensate reactive power effectively, eliminate harmonic drastically and balance load imbalance current availably, and improve reliability and security of electrified railway greatly.**

***Index Terms*—electric railway, traffic safety, harmonic suppression, power quality, passive power compensation, negative sequence current**

I. Introduction

With the development of electrified railway, electric locomotive was applied in railway transportation more and more widely. Because multi-section full-wave rectifier or bridge rectifier was adopted in the power supply manner, harmonic, reactive power and negative sequence current will be produced in the power supply system. And they can be harmed security on power system network, production and manufacture badly and more then electrified railway security and reliability in the railway transportation [1]. So harmonic, reactive power and negative sequence current will be eliminated or removed in the power supply system. Power quality will be improved. And then enhanced power factor and decreased negative sequence current and harmonic. And so the reliability of power supply system can be increased and the efficiency of electric power equipment can be gained. So that research and improvement power supply network environment factor and increase electric management manner is of important practical significance. Implementing above function will produce enormously society and economy benefit.

In the paper, the measures and means of power quality control were introduced, analyzed and compared in detailed. The advantages and disadvantages of the measures and means can be point out. Aiming at the measures and means existing power quality control, project of integrated suppressive were put forward on controlling power quality for electrified railway. In order to achieve real-time detection and compensation of electrified railway power quality, the inspection method of designated degree harmonic current is adopted and the rapidly changing specific degree harmonic current composition of traction load is detected. The rapidly changing active power and reactive power ingredients are detected based on hilbert digital phase-shifting filter. Through adjusting magnetron SVC device the imbalance load is balanced. This new injection-type hybrid active power filter combined with magnetron SVC make to compensate effectively passive power, eliminate drastically harmonic and improve load imbalance current of electrified railway.

II. Characteristics of Electric Railway

Generally speaking, harmonic is sine wave component with electric period. The frequency of harmonic is the integral multiple of basic wave. So it is generally named as high order harmonic. Electric railway harmonic has following characteristics.

Manuscript received August 2, 2008; revised January 30, 2009. This paper was presented at the 2008 Workshop on Power Electronics and Intelligent Transportation System, Guangzhou, China, August 15-18.

The authors are with School of Electrical Engineering, Wuhan University, Wuhan , 430072, China. (email: ecjtuxxz@sina.com).

The project is sponsored by scientific research fund of east china jiaotong university. Project number 06ZKDQ05.

doi:10.4304/jcp.5.3.464-470

(1)Stochastic volatility: The harmonic current of traction power is varied rapidly with the load of fundamental wave. The harmonic current is resulted to change in the certain range.

(2)Phase distributed widely: The initial phase angle of each order harmonic is stochastic variable with high variance. Their harmonic vector is distributed widely in the 4 quadrants of complex plane.

(3)Penetrability power of high voltage: High voltage is supplied to the electric railway. The kind of consumer is a few correspondingly. Harmonic of every order is penetrated to overall electric power through the high voltage system. Harmonic penetrability is not obstructed from coupling manners of transformer.

(4)Steady state of odd order: Odd order harmonic is brought only in single phase commutating load of steady state running. Even order harmonic is brought only in flow current. Principal harmonics of electric railway are the 3^{rd}, the 5^{th} and the7^{th}. The 3^{rd} harmonic is mainly component among them. The higher order of harmonic is, the less of component of harmonic is. And it will be only 1% if the order is the 15^{th} .

From the above, the harm caused by electric railway harmonic to the electric networks can be listed mainly as follows:

(1) Shunt-wound resonance: resonance circuit of certain harmonic is structured by distributing capacitance face to ground and loop inductance of traction networks, when harmonic current returns to the system through traction networks. The harm to the security of system is produced at the same time.

(2) The harm to traction transformer: harmonic voltage will brought in the power because the harmonic current flows through the traction transformer. And additional iron loss and copper loss are caused by high order current and voltage of harmonic. Meanwhile the effective capacitance of transformer is reduced and efficiency is decreased.

Besides these mentioned above, the high order harmonic current will bring accidental or error action of relay protection. And the secure operation of power system is affected. Meanwhile the generator, electric instrument, electric isolation and auto-control device will be influenced. Therefore, effective measure should be taken to wipe out or reduce the content of harmonic in traction power system.

III. MAIN METHODS OF HARMONIC SUPPRESSION AND EXISTING PROBLEMS

At present, there are two thoughts in the harmonic suppressive problem. First, harmonic source was reconstructed. This measure is fundamentality manner and is adopted widely in practical. Second, when harmonic source was reconstructed, but harmonic is not eliminated in the power supply system and satisfied with demand. The equipment of eliminated harmonic will be added in the system to absorb harmonic brought by harmonic source. Presently, the major equipment of eliminated harmonic is power supply filter in supply network system. And more power supply filter is divided into active power filter and passive power filter two manners.

LC passive power filter is introduced in the power supply system to resolve or eliminate harmonic. The method of LC passive power filter can be not only compensate harmonic but also compensate passive power. On account of LC passive power filter structure simple, maintenance convenience and resistance high voltage, it can be used in all compensate power supply system. But there is some shortages existing in the manner. Show as following:

(1) Impedance and operation state of power system network will influence characteristic of LC passive power filter and compensation efficiency can be influenced. When the system impedance structure of power supply system or operation state was changed. Compensate efficiency is not meet with demand of user and power system.

(2) LC passive power filter is easy to produce parallel resonance with power system. And so the harmonic will be magnified to LC passive power filter over loading or damage [2].

(3) In the compensated course, given or specifically frequency harmonic can be eliminated effectively. Purpose of compensate is restrained. So improvement of LC passive power filter characteristic is extraordinary necessary.

Active power compensated technology is used active power filter to eliminate or suppress harmonic. The method is development trend and direction. The basal thought is check and measure harmonic current in the compensated object and produce electric current by active power filter which electric current value is equal to compensate electric current and electric current phase is opposite to it. Electric current by active power filter is injected to power supply system to counteract harmonic current brought by load harmonic current. And so there is only base current in the power system. There are some advantages of active power filter relative to passive power filter as following:

(1) The methods can be realized harmonic compensation with the load current variety. It is a dynamic harmonic compensation. It is of response time little and track compensation with frequency, value and passive power of harmonic current. Dynamic harmonic compensation is with the load harmonic current variety.

(2) When it compensates passive power, the energy storage component is not adopted in the system of structure. In the compensated course, capability value of energy storage component is not big.

(3) The compensate efficiency is not influence by impedance and operation state of power system network and frequency. Frequency is changed with loading current [3] .

(4) The active power filter can used not only a certain harmonic and passive power source to compensate solely but also multi- harmonic and passive power source to compensate synchronously.

And but there are some disadvantages or problems in the active power filter system.

(1) Based voltage of alternating current power is inflow directly to PWM convertor. So the method requires big capability PWM convertor to adapt loading electric current variety. At present, big capability PWM convertor is not realized with low-consume and fast-response.

(2) Comparing with passive power filter, the active power filter installation and maintenance cost are more relatively.

Ⅳ. Main Methods of Passive Power Compensation and Existing Problems

In the early period, synchronous condenser is a typical equipment of compensation equipment of passive power. Synchronous condenser can compensate not only given passive power, but also dynamic compensate mutative passive power. With the development of control technology, control effect has increase greatly in practical application.

Cost of parallel high voltage capacitor is low comparatively comparing with synchronous condenser in the condition of the same purpose. So the parallel high voltage capacitor is used in the power supply widely. But the effect is not satisfied in the variational loading current.

Advanced Static VAR Generator (SVG) is a typical equipment of compensates equipment based on power and electronic technology. Advanced static VAR generator is only used smaller capability capacitor to maintain its operation voltage in the direct current side. Fixed capacitor (FC) adding tunable reactor (TCR) is a typical structure of advanced static VAR generator. Control characteristic of tunable reactor is character of saturation magnetization with standing out by magnetron-advanced static VAR generator. SVG can be control through change trigger angle of thyristor of saturation electric controller with sequence adjusting passive power. The device can be absorbed passive power in the capacitive or the inductive characteristic.

Active power filter is a new type compensation system of harmonic, reactive power and negative sequence current. In the power supply system, active power filter is adopted to gain more superiority compensation purpose then other methods.

There are some problems as follow in the compensated methods of passive power at present:

(1) That the power supply system is adopted synchronous condenser to compensate passive power is out of season with high servicing cost in all senses.

(2) Only given passive power can be compensated effectively using parallel capacitor.

(3) Tunable reactor device used by control-phased theory to control trigger angle of thyristor. With modulating fundamental wave passive power in the dynamic, harmonic can be product in a great deal [4].

(4) SVG is an advanced harmonic compensate device. If in the system PWM control technology can be adopted, output harmonic current can be lessen in a certain extent. In the practical, because of reliability, cost and maintenance and so on factors, its application is limited.

(5) Superiority of active power filter is reproachless in the application. Active power filter (APF) can be used in low-voltage supply system in the Japan. Active power filter is just of research and experimentation period in our country.

Ⅴ. Suppression Methods of Negative Sequence Current and Existing Problems

Because of dissymmetry three phase load current can be cause unbalance three phase voltage. This problem can be resolved by using as following manners.

(1) Three phase dissymmetry load can be distributed different power supply position to reduce imbalance problem caused by centralization connection [5].

(2) Dissymmetry three phase load can be distributed reasonable different phase, and made loading balance.

(3) Dissymmetry three phase load can be distributed higher voltage power supply, and made short circuit capacitance sufficient more. For example, when short capacitance is more 50 times than single-phase load capacitance, the degree of voltage imbalance is less 2 percent.

(4) Balance device or equipment is used in the power supply system to eliminate imbalance.

At present, resolving this problem can be using as following two methods in the practical:

(1) Using transformer with specifically connection to balance load current such as Scott and reverse Scott connected transformer.

(2) More high voltage was adopted in the power supply. In the practical, 110KV voltage supply can be replaced by using 220KV voltage supply in the system.

Although above two kind methods can be resolve imbalance problem in a certain extent. But negative sequence current can not eliminate or remove thoroughly in these kinds.

Ⅵ. Analysis of Suppression Project

At present, there are 5 kinds of project or methods of synthesis suppression, which can suppress harmonic, compensate passive power and eliminate negative sequence current. Table Ⅰ is function compared of compensated devices.

TABLE Ⅰ.
FUNCTION COMPARED OF COMPENSATED DEVICES

	Suppress harmonic	Compensate passive power	Eliminate negative sequence current
Passive power filter	√	√	√
Active power filter	√	√	×
Synchronous condenser	×	√	×
Static VAR generator	×	√	√
Static VAR compensator	×	√	√

As following results can be received from the Table Ⅰ:

(1) Superiority of active power filter is inculpable in the application from technology. It can resolve all problems of power quality brought from point of view electrified railway.

(2) Static VAR Compensator (SVC) is optimal project to eliminate negative sequence current and dynamic passive power from point of view economy.

(3) Passive power filer is optimal project to eliminate harmonic from point of view reliability. Magnetron SVC is optimal method to eliminate negative sequence current and dynamic passive power.

Ⅶ. SYNTHESIS CONTROL SCHEME

Synthesis Control is a development thought in the control power quality. Whereas the advantage of passive power filter, active power filter and Static VAR Compensator in the technology, reliability and economy, a new injection-type hybrid active power filter(HAPF) combined with magnetron SVC make to compensate effectively passive power, eliminate drastically harmonic and improve load imbalance current. Principle Circuit is shown on Fig.1.

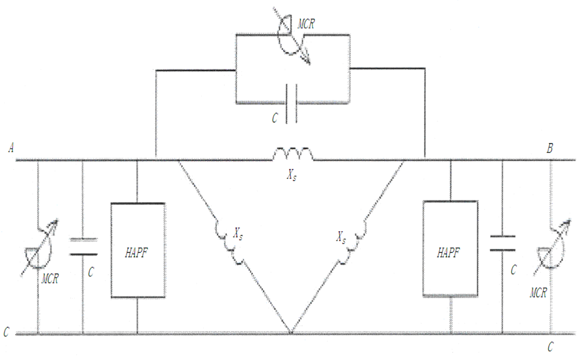

Figure 1. The functional block diagram of Comprehensive compensation

Magnetron SVC can compensate reactive power which is composed of magnetron reactor (MCR) and fixed capacitor (FC). Take into account each group reactor capacity configuration of magnetron SVC is different, and single-phase MCR is now widely used in electrified railway reactive power compensation system because of its technology reliability, accordingly three single-phase MCR are adopted in device of magnetron SVC compensation device.

Magnetron SVC depends on the control angle regulation of the magnetron reactor, reactor capacity is smoothly adjusted through changing control angle of thyristor. According to survey results the compensated capacity of compensation device is real-time calculated by different configurations of magnetron SVC between a phase and b phase or b phase and c phase or c phase and a phase. Changing trigger angle of thyristor, when reactive power is compensated, load imbalance current is improved synchronously. Load harmonic of electrified railway is suppressed by hybrid active power filter. Capability and cost of HAPF are reduced consumedly, and the reliability of the system is improved. So from the reliability, economic, technical point of view the comprehensive scheme is the best compensated scheme.

A. Harmonic Current Detection Method

Harmonic current detection method is the means which all harmonic current will be the sum total harmonic current i_{ah} after parallel computing every harmonic current, namely, it is compensated current command signal. PWM pulse signal is produced from current controller, when instruction signal of compensating current is made, and to control the inverter produce a harmonic current with equal magnitude and opposite polarity of actual harmonic current. The current in the power grids contains only fundamental component. The compensated current is compared with the actual compensation current to form a closed-loop control of the current track. The Suppression principle of harmonic current showed in Fig.2

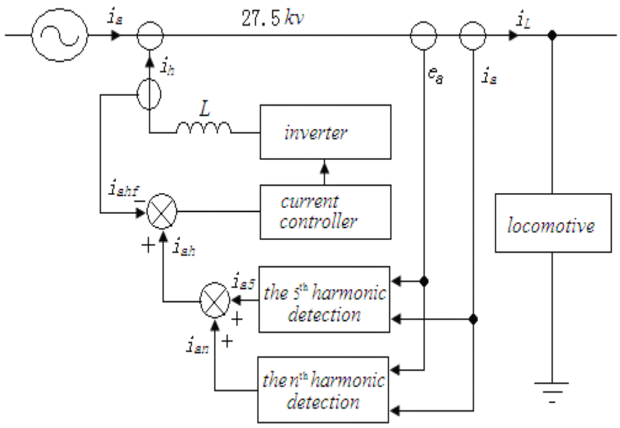

Figure 2. Harmonic suppression principle of electric railway

As to detecting harmonic current of three-phase circuit, the three-phase signal should be changed into mutually vertical α and β signal of two-phase [6]. And then its rotation transformation can be taken. Method mentioned above is applied in the single phase system. Auxiliary current with delayed 90º to fundamental current is formed. Take detection of the 5th harmonic current for example, detecting principle is showed in Fig.3.

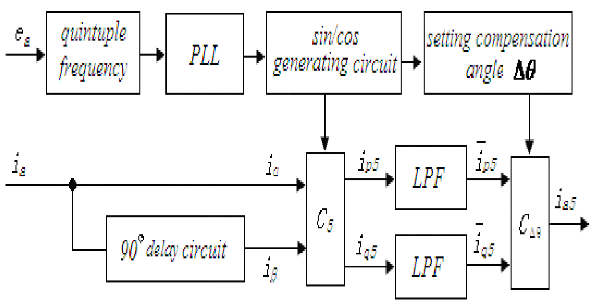

Figure 3. Detecting principle of single-phase 5th harmonic

The calculation steps are following:

(1) Instantaneous voltage frequency of single phase is multiplied by 5 in frequency scope. Sine signal $\sin 5\omega t$ and cosine signal $\cos 5\omega t$ which have the same phase as

e_a should be realized through phase-locked loop and generator of sine and cosine. And then transformation matrix C_5 may be gained as follows:

$$C_5 = \begin{bmatrix} -\sin 5\omega t & \cos 5\omega t \\ \cos 5\omega t & \sin 5\omega t \end{bmatrix} \quad (1)$$

(2) Instantaneous value i_a is set as i_α . And then auxiliary current i_β is formed which delayed 90º to fundamental current i_α .

(3) Reactive power current i_{q5} and active power current i_{p5} component of each order harmonic could be received by tow-phase current i_α and i_β through transformation matrix C_5 . It is expressed as follows:

$$\begin{bmatrix} i_{p5} \\ i_{q5} \end{bmatrix} = C_5 \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (2)$$

(4) Reactive power $\bar{i}_{q5}$ and active power current $\bar{i}_{p5}$ of the 5th harmonic current might be received after i_{p5} and i_{q5} flow through LPF filter. The 5th harmonic current is given through transformation matrix $C_{\Delta\theta}$. It is expressed as follows:

$$i_{a5} = C_{\Delta\theta} \begin{bmatrix} \bar{i}_{p5} \\ \bar{i}_{q5} \end{bmatrix} \quad (3)$$

As to digital controller, at least operation time ΔT of one sampling periodical is demanded. Meanwhile output voltage of PWM inverter can be established in time of ΔT. So at least a delay-ΔT is existed from current sampling to harmonic compensation. In the delay time of ΔT, angular frequency of fundamental wave is set as ω. Rotational angle of nth order harmonic in time of ΔT is given as follows:

$$\Delta\theta = n\omega\Delta T = 2n\pi f\Delta T \text{ (rad)} \quad (4)$$

When the delay time is not considered in design, then identical transformation does not exist after rotation. Certain harmonic of high order will be formed positive feedback in worse condition. This will influence the secure operation of power system. In this paper, angle $\Delta\theta$ is added to $5\omega t$ in C_5^{-1} matrix to use compensation. Its compensate matrix is expressed as follows:

$$C_{\Delta\theta} = \begin{bmatrix} -\sin(5\omega t + \Delta\theta) & \cos(5\omega t + \Delta\theta) \\ \cos(5\omega t + \Delta\theta) & \sin(5\omega t + \Delta\theta) \end{bmatrix}^{-1} \quad (5)$$

B. Reactive Power Detection Method

Based on hilbert digital phase-shifting filter the reactive power measurement principle diagram is shown in Fig.4.

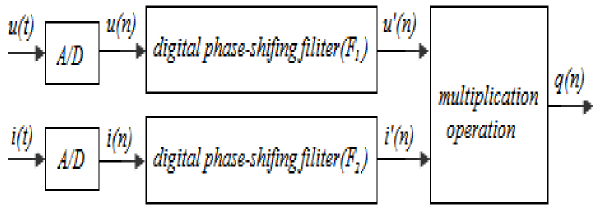

Figure 4. Reactive power detection principle diagram

Firstly, a certain phase voltage and current signals of the power grids are implemented A / D conversion at the same sampling rate, and discrete digital voltage signal $u(n)$ and digital current signal $i(n)$ are gained. Secondly, a pair of above digital signals is carried out phase shifter processing by F_1 and F_2 filter respectively. And a pair of complex digital signal $u'(n)$ and $i'(n)$ are made, the phase angle is 90° between the fundamental wave of the voltage and current and harmonic components. Then the two complex signals are multiplied to make instantaneous reactive power $q(n)$ .Finally, the reactive power Q is made after $q(n)$ is filtered.

C. Balancing Asymmetric Load

Any non-grounding Y connected load can be expressed as Δ connected load through Y-Δ transformation. Ideal load compensator is substituted using an arbitrary three-phase passive admittance. When the passive admittance is paralleled with the load, it is equal to a real symmetric load toward power supply. The passive admittance is combined with power factor correction to form a ideal compensation network with Δ connected fashion, which each branch of triangle has three parallel compensated susceptance [7].

$$\begin{aligned} B_r^{ab} &= -B_1^{ab} + (G_1^{ca} - G_1^{bc})/\sqrt{3} \\ B_r^{bc} &= -B_1^{bc} + (G_1^{ab} - G_1^{ca})/\sqrt{3} \\ B_r^{ca} &= -B_1^{ca} + (G_1^{bc} - G_1^{ab})/\sqrt{3} \end{aligned} \quad (6)$$

A cycle of P and Q are easily gained using instantaneous reactive power theory. Virtual value of lines voltage can be obtained through the voltage sensor. Therefore, the compensated susceptance can be calculated, and mutative load can be fleetly conducted real-time tracking, and the compensation device capacity is rapidly adjusted, three-phase imbalance voltage and current are improved by compensated voltage and current. Because of the special nature of electrified railway, traction arm is usually a phase and b phase. There is load between a phase and c phase or b phase and c phase, thus, there is nothing between a phase and b phase. $P_{ab} = Q_{ab} = 0$. Q is considered the inductive reactive power. The compensation capacity of the device is set as follows:

$$Q_r^{ab} = -(\frac{U_{ab}^2}{U_{ca}^2}P_{ca} - \frac{U_{ab}^2}{U_{bc}^2}P_{bc})/\sqrt{3}$$
$$Q_r^{bc} = -Q_{bc} + \frac{U_{bc}^2}{U_{ca}^2}P_{ca}/\sqrt{3} \quad (7)$$
$$Q_r^{ca} = -Q_{ca} - \frac{U_{ca}^2}{U_{bc}^2}P_{bc}/\sqrt{3}$$

From (6) and (7), it can be found that the compensation capacity of the device is impacted by active power and reactive power between any two phases, that is, the compensation capacity may be a positive or a negative. If a group magnetron reactor and fixed capacitors (magnetron SVC) are shunted between every two-phase (a phase and b phase, b phase and c phase, c phase and a phase), the compensated capacity is dynamically adjusted with mutative load within the limits of requisite capacity. Each of the compensation devices can be produced capacitive reactive power or inductive reactive power, thereby, the reactive power of power network is compensated, and the power factor is increased, synchronously the asymmetry load of the three-phase is greatly improved.

D. Hybrid Active Power Filter

In Fig.5, branch L_1-C_1 produces series resonance in the fundamental wave frequency. In the same way, branch L_3-C_3, branch L_5-C_5, branch L_7-C_7 and branch L_{11}-C_{11} produce series resonance respectively in 3^{th} and 5^{th} and 7^{th} and 11^{th} harmonic frequencies. The hybrid active power filter make use of resonant characteristics of LC circuit to structure injection loop, thus inverter almost does not bear the fundamental voltage, and the capacity of the inverter is greatly reduced. Fundamental wave branch produces resonance in the fundamental frequency, the branch is similar to a short circuit, and LC filter can compensate reactive power [8]. The APF and fundamental resonant branch are in series, the series branch is equal to impedance in harmonic frequencies, which is in series with power supply. At this point, load harmonic current is injected passive power filter circuit. Filtering effect of passive filter is greatly improved.

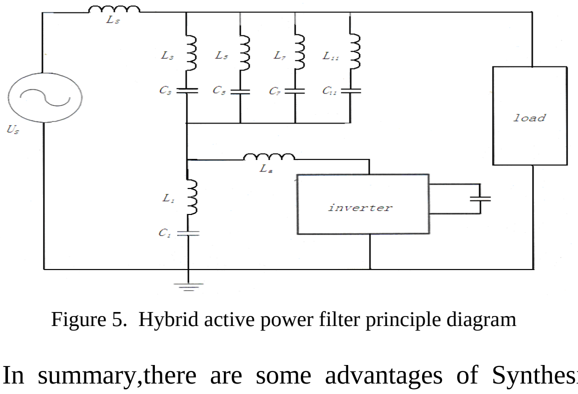

Figure 5. Hybrid active power filter principle diagram

In summary,there are some advantages of Synthesis Control scheme as following:

(1) Injected-type active power filter is not influenced by fundamental wave voltage and passive power current. Capacity and cost is small in a certain extent.

(2) This methods cannot only eliminate harmonic current feed power system but also repress harmonic current caused by voltage aberration.

(3) Control system is belong to open loop control with instability in some extend.

(4) MCR operation state used limited magnetron maturation and autotransformer direct current excitation. Brought harmonic by MCR is reduced greatly. Its power consumption is small and response speed is rapid.

(5) Compensated power can be regulated continuously with evident purpose, high reliability and maintenance expediently.

Ⅷ. CONCLUSIONS

Comprehensive compensation scheme make use of the advantages of MCR and HAPF. Reactor capacity is smoothly adjusted through changing control angle of thyristor. When reactive power is compensated, synchronously load imbalance current is eliminated. The voltage of APF bearing is reduced through resonant principle, the capacity and cost of equipment are reduced, and work efficiency and reliability are improved distinctly. Active power filter (APF) is used to remedy filtering effects of passive power filter (PPF), and absorb the remaining harmonic, and prevent PPF from overload. Practice has proved that the scheme can not only suppress harmonics, but also compensate reactive power and negative sequence current. Compensation effect is prominent, and operation is safe. The traction power substation reliability and safe operation of electrified railway are improved greatly.

ACKNOWLEDGMENT

The outlays of this research are sponsored by scientific research fund of east china jiaotong university. And the serial number Of research subject is 06ZKDQ05. I thank correlative favors by department of scientific research of east china jiaotong university. And I thank my supervisor professor Chen Baichao very much.

REFERENCES

[1] Jun-li Zhao, and Jun Yang, and Yun-qing Pei,“Study on active filter of electrified railway,” *Electric drive for locomotive*,Vol.5,2008, pp.9-14.

[2] Yan Cheng, and Di-chen Liu,“Study on harmonics restraining and compensating in active filter system based on Matlab,” *Micro-computer information*,Vol.5,2007, PP.39-42.

[3] Chao Zhang, “An algorithm for random harmonic current detection of active power filter”, *Electric machines and control*, Vol.6, 2003, pp.252-255.

[4] Han Xue-jun, Wang Jing-hao, “Research on integrated compensation of three phase unbalance load”, *Power system technology*, Vol.30, 2006, pp.289-291.

[5] Hong Zheng, and Zhen-qing Yi, “Harmonic analysis and reckoning of traction transformer station for electrified

railways", *Journal of jiangsu university (Natural Science Edition)* , Vol.24, 2006, pp.76-70.
[6] Yue Wang, and Jun Yang, and Zhao-an Wang, "Study on hybrid power filter used in electrified railway system", *Proceedings of the CSEE*, Vol.23, 2003, pp.23-27.
[7] Zhang Ya di, "Study of compensating three phase imbalance of electrified railway power based on the mcr with two-stage iron core," *Electric drive*, Vol.37, 2007, pp.52-55.
[8] G.Choe and M.Park, "A new injection method for ac harmonic elimination by active power filter," IEEE.Trans. Ind. Electron, Vol.25, Feb. 1988.

Xiangzheng Xu was born in Jiangxi Province, China, on January,1965. He received the B.S. and M.S. degrees from east china jiaotong university of electrical engineering, Nanchan, China, in 1987 and 1995 respectively. He is currently doing graduate work for the Ph.D. degree at Wuhan University.

His research interests are power electronics, PWM control techniques for inverters and harmonic reduction methods at power systems.