TEST Engineering & Management

July - August 2020
ISSN: 0193-4120 Page No. 5563 - 5571

Research on Reactive Power Compensation and Harmonic Suppression of Electrified Railway

Yuxin Liu[1], Zheng Zhou[1,*]
[1]Zhengzhou Railway Vocational & Technical College, Zhengzhou, Henan, China, 450018

Article Info
Volume 83
Page Number: 5563 - 5571
Publication Issue:
July - August 2020

Article History
Article Received: *25 April 2020*
Revised: *29 May 2020*
Accepted: *20 June 2020*
Publication: *28 August 2020*

Abstract

Electrified railway has prominent and serious harmonic and reactive power problems, which lead to the increase of electrical loss and reduce the output power of electrical equipment, which seriously interferes with the normal operation of electrical equipment and even leads to the damage of electrical equipment. Therefore, the research on reactive power compensation and harmonic suppression of electrified railway has important practical value. Based on this, this paper first analyses the application status of harmonics restraining and reactive compensating technology in electrified railway, then studies the design method of harmonics restraining and reactive compensating in electrified railway, and finally gives the simulation strategy of harmonic control and reactive power compensation of electrified railway.

Keywords: *Reactive Power Compensation, Harmonic Suppression, Electrified Railway;*

1. Introduction

At present, with the rapid development of social economy, China's railway construction has made remarkable achievements, especially China's high-speed railway technology has obtained the international leading position, and its construction and operation mileage has ranked first in the world[1]. With the gradual completion of China's railway electrification transformation, electrified railway has become the standard configuration of railway construction, and the electrified railway will face more prominent and serious harmonic and reactive power problems, which will cause serious harm to the electrified railway, as shown in Table 1 below. In order to ensure the normal operation of electrified railway and its transportation advantages, it is necessary to carry out reactive power compensation and harmonic suppression.

Table 1. Influence of harmonic and reactive power problems.

Harmonic		Reactive power	
Field	Influence	Field	Influence
Grid element	Reduce electrical efficiency	Power supply	Loss increase
Transmission line	Line fault, equip damage	Power system	Reduced efficiency
Grid voltage	Distortion	Trans voltage	Violent fluctuations
Electrical instruments	Failure, misalignment	Electric equip	Damage
Communication circuit	Disturbed	Power supply	Reduced

The main reason why electrified railway will produce more prominent and serious harmonic and reactive power problems is that the load with typical characteristics as shown in Figure 1 will be generated during the operation of electrified locomotive, which will lead to harmonic pollution and low power factor. Harmonic pollution will lead to the increase of electrical loss and reduce the output power of electrical equipment, which seriously interferes with the normal operation of electrical equipment, and even leads to the damage of electrical equipment[2].

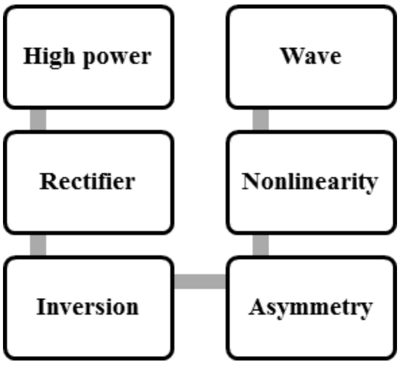

Figure 1. Operating load characteristics of electrified locomotive.

Thanks to the advantages of electrified railway in many aspects, the electrified railway has obtained rapid development in recent years[3]. The research on harmonic and reactive power of electrified railway is not only related to the reliability of electrified equipment, but also has important value for the sustainable development of electrified railway. Although reactive power compensation and harmonic suppression for electrified railway are two relatively independent processes and compensation measures, there is complementary correlation between the two measures, which is embodied in the following table 2.

Table 2. Relationship between reactive power compensation and harmonic suppression.

Associated parameters	Association	Influence
Harmonic	Definition and harmonic of reactive power	Reactive power of load and grid
Harmonic	Harmonic and reactive power generator	Reactive power consumption by power electronic devices
Reactive power	Harmonic and reactive power compensation device	Reactive power compensation by power filter

At present, the harmonics restraining and reactive compensating measures of electrified railway are mainly realized by adding passive filter device, static var compensator and active power filter, but these different devices have their own inherent advantages and disadvantages and typical characteristics[4]. Therefore, in order to achieve the maximum compensation and inhibition effect under the limited investment and resource constraints, it is often a combination of several means to maximize the cost and benefit. Therefore, the research on reactive power compensation and harmonic suppression of electrified railway has important practical value.

2. Application status of harmonics restraining and reactive compensating technology in electrified railway

As the harmonic and reactive power problems of electrified railway will have serious consequences and impacts, it is necessary to take relevant technologies and measures to carry out harmonic suppression and reactive power compensation. At present, the harmonics restraining and reactive compensating of traction power supply for

Published by: The Mattingley Publishing Co., Inc.

July - August 2020
ISSN: 0193-4120 Page No. 5563 - 5571

electrified railway locomotive are mainly carried out by optimizing and reforming the motor, compensating harmonic and reactive power, etc. These two strategies and ideas have their own advantages and disadvantages and characteristics, so as to achieve centralized governance and improvement of reactive power and harmonic problems.

At present, the harmonics restraining and reactive compensating technology of electrified railway is mainly realized by installing harmonic filtering and reactive power compensation devices, including active power filter system and passive power filter system[5]. The former includes the application of separate active power filter and hybrid use of active power filter. The latter includes the installation and installation of vacuum switch switching passive power filter and thyristor switching passive power filter.

2.1. Application status of harmonic suppression technology in electrified railway

In the technology and equipment of harmonic centralized treatment of electrified railway, the fixed capacitor bank and reactor are used for harmonic control, thus a typical capacitor compensation device is constructed. Secondly, the voltage is reduced and the compensation capacitor bank is branched to realize harmonic control. Secondly, based on the fixed capacitor device, the shunt magnetic saturation reactor is constructed to cancel the over compensated capacitive reactive power, so as to realize the harmonic control. In addition, multiple harmonics can be filtered out based on voltage regulator adjustment, but it is necessary to pay attention to the phenomenon that the harmonic exceeds the standard when the load is too large.

2.1.1. Influence of harmonics on electrical equipment

The influence of harmonics on the electrified railway electrical equipment is shown in the following aspects: increasing the loss; reducing the service life; making the operation performance worse. The harmonic voltage produces harmonic current in the winding, which makes the winding heat up and produces heat loss. The three-phase total harmonic loss is as follows:

$$P_{total} = \sum P_n = \frac{3R_{12}}{\sqrt{2}(\omega_1 L_L)^2} \sum_{n=2}^{\infty} \frac{U_n^2}{n^{3/2}} = \frac{3R_{12}}{\sqrt{2}(\omega_1 L_L)^2} U_{1(2)eq}^2 \qquad (1)$$

The loss caused by harmonics can be equivalent to the negative sequence component of a fundamental wave. Therefore, $U_{1(2)eq}$ is called equivalent fundamental negative sequence voltage. Its physical meaning is that the loss caused by all harmonics is equivalent to the loss caused by a fundamental negative sequence voltage[6]. This voltage is $U_{1(2)eq}$, and the corresponding negative sequence equivalent resistance is as follows:

$$R_{1(2)eq} = \frac{R_{12}}{\sqrt{2}} \qquad (2)$$

If the frequency of harmonic current is close to the natural vibration frequency of stator parts, it may cause strong vibration of motor and cause damage of motor shaft of railway traction locomotive due to fatigue.

2.1.2. Disturbance of harmonics on secondary equipment of electrified railway

The main influence of harmonics on the secondary equipment of electrified railway is to disturb its normal working state. Such as measurement accuracy, action reliability, etc. In the level of disturbance to electrified railway measuring instruments, the relationship between the error of voltmeter and frequency characteristics under distorted waveform is as follows:

$$\gamma = \pm \frac{U_1^2 \gamma_1 + U_2^2 \gamma_2 + U_3^2 \gamma_3 + \cdots}{U^2} \times 100\% \qquad (3)$$

In which, γ is the relative error of the voltmeter under the distorted waveform; U is the effective value of the voltage under the distorted waveform; U_1 and U_2 are the effective values of the voltage of

Published by: The Mattingley Publishing Co., Inc.

each harmonic component; and γ_1 , γ_2 ,…are the relative error of each harmonic frequency determined by the frequency characteristics. Therefore, the relative error under the distorted waveform depends not only on the frequency characteristics, but also on the content of harmonics.

The influence of harmonic on the induction instrument of electrified railway is that the ferromagnetic elements of the induction voltmeter have nonlinear characteristics, so when the power frequency voltage and current of pure sinusoidal wave are input, there are still some harmonic components in the winding and turntable of the voltmeter. These harmonic components interact with the harmonics contained in another winding to generate torque, which increases or reduces the measurement reading.

In the level of harmonic disturbance to the relay protection device of electrified railway, the appearance of harmonic will cause great measurement error in case of fault, and may refuse to operate or misoperate in serious cases[7]. Using digital impedance relay and digital filtering to eliminate the influence of harmonics, good results have been achieved.

Due to the large harmonic content in the fault current, if there is no filter device, the possibility of misoperation is large. Under non fault condition, the waveform of secondary current is seriously distorted, which may exceed the setting value of the over-current relay and cause maloperation. For the differential protection level of transformer, when no-load closing, the secondary side is open circuit, and the serious imbalance of side current will also make it act, which makes the internal fault of electrified railway transformer expand due to delayed tripping.

2.2. Harmonic suppression technology and measures

In order to reduce the adverse effects of harmonics on electrified railway, appropriate technical measures shall be taken for harmonic source itself or nearby, as shown in Table 3 below. The selection of specific harmonic suppression measures should be based on the comprehensive comparison of harmonic level, effect, economy and technology maturity.

Table 3. Harmonic suppression technology and measures.

Measures	Contents	Evaluation
Increase the pulsation converter	Transformation of converter	Reduce harmonic Device complexity increased
Installation of AC filter	Installation of high pass filter branch	Reduce harmonic Simple maintenance
Improving harmonic sources	Concentrated harmonic complementary device	Reduce the influence of harmonics
Installation of series reactor	Add series reactor	Reduce harmonic Simple maintenance
Improve 3 phase unbalance	Find out the cause of 3-phase unbalance	Reduce harmonic generation Reduce equipment loss

In addition, the AC passive filter is an effective method to suppress harmonics. The filter can present low impedance to a single frequency or within a frequency range, and can absorb the harmonic current equivalent to the resonance frequency in the power grid, and has the advantages of simple structure, reliable operation and convenient maintenance.

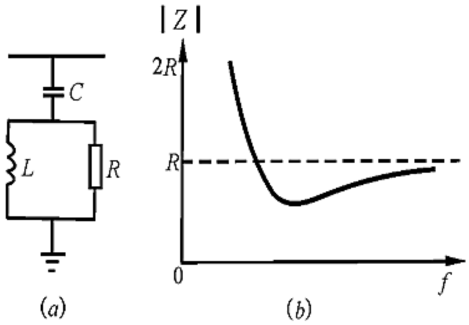

Figure 2. The operation principle of high pass filter.

The principle of high pass filter is shown in Figure 2 above, where L is bypassed by R, and its combined impedance cannot exceed R value. Therefore, when the frequency exceeds a certain critical value, it shows low impedance characteristics in a wide frequency range.

2.3. Application status of reactive power compensation technology

Reactive power compensation plays an active role in improving the power factor of power grid, reducing power loss and improving the efficiency and environment of electrical system in the power supply system of electrified railway. It can be seen that reactive power compensation device plays an important role in the power supply system of electrified railway. In order to reduce the power loss of electrified railway power supply system and improve the quality of power grid, it is necessary to scientifically apply reactive power compensation device to avoid voltage fluctuation and harmonic interference.

2.3.1. The effect of reactive power compensation

In order to improve the voltage quality, the current in the electrified railway line is divided into active current and reactive current, as shown in following formula:

$$\Delta U = 3 \times \left(I_a R + I_r X_l \right) = 3 \times \frac{PR + QX_l}{U} \quad (4)$$

In which, R is the total resistance of the line, Ω is the line inductive reactance. After increasing the power factor, the reactive power Q transmitted on the line can be reduced. If the active power is kept unchanged and R and XL are fixed values, the lager the reactive power Q is, the bigger the voltage loss is, thus improving the quality of power supply voltage. Secondly, it can improve the application rate of electrified railway transformer, reduce investment, carry more load, reduce investment and expenditure of power transmission and transformation equipment, and avoid power factor is too small. In addition, it helps avoid the loss of reactive power transmission and distribution, and help avoid the transmission cost and improve the transmission efficiency.

2.3.2. The way of reactive power compensation

The main effect of reactive power compensation is to improve power factor to avoid equipment capacity and power loss as much as possible, balance voltage and improve power supply quality, improve transmission stability and transmission capacity in long-distance transmission, and stabilize active and reactive power load. Installation of shunt capacitor for reactive power compensation can limit the transmission of reactive power in the power grid, reduce the voltage loss of electrified railway lines, and improve the voltage quality of distribution network.

The reactive power compensation of electrified railway mainly includes centralized compensation, decentralized compensation and local compensation. Among them, centralized compensation can reduce the reactive power loss of electrified railway lines and improve the quality of power supply voltage. Decentralized compensation and centralized compensation have the same advantages, but the reactive power capacity is small and the effect is obvious. The local compensation can improve the power factor of the power supply circuit. The selection of reactive power compensation for electrified railway is usually carried out according to the principles shown in Table 4 below.

Published by: The Mattingley Publishing Co., Inc.

July - August 2020
ISSN: 0193-4120 Page No. 5563 - 5571

Table 4. The selection of reactive power compensation for electrified railway.

Combination mode	Leading mode
Centralized compensation and decentralized compensation	Decentralized compensation
Adjustment compensation and fixed compensation	Fixed compensation
High voltage compensation and low voltage compensation	Low voltage compensation

3. Design method of harmonics restraining and reactive compensating for electrified railway

The electric locomotive of electrified railway will produce large load fluctuation in the process of operation, especially when the locomotive runs under heavy load and no-load, so it is necessary to calculate the average value of reactive power based on the specific period. The reactive power of electrified railway is closely related to power factor. Based on the average reactive power value of electric arm load after parallel filter, the power factor under compensation is obtained.

Based on the characteristics and principles of reactive power compensation of electrified railway, the reactive power of load is compensated by the filter of reactive power compensator. However, there are many limitations in the actual operation of electrified railway. These practical engineering application limitations are embodied in the following aspects: the filter cannot realize stepless compensation, the cost is not controlled due to too many filter groups, the input is large, the switching frequency leads to low reliability, and the filter requirements of the filter are difficult to realize and meet.

3.1. Design of single tuned filter

For *nth* order single tuned filter, R_{fn} is the total resistance of filter loop considering C and L losses under *nth* harmonic.

$$Z_{fn} = R_{fn} + j\left(n\omega L - \frac{1}{n\omega C}\right) \quad (5)$$

When,

$$n\omega_r = \frac{1}{\sqrt{LC}} \quad (6)$$

The ideal resonance condition is achieved. If ω_r is equal to rated power frequency angular frequency ω_1, the resonant conditions of *nth* harmonic are as follows:

$$n\omega_1 = \frac{1}{\sqrt{LC}} \quad (7)$$

When the resonance impedance reaches the minimum value $Z_{fn} = R_{fn}$, then the *nth* harmonic current mainly flows through the electrified railway filter, which reduces the *nth* harmonic current flowing into the power grid, so as to suppress the *nth* harmonic.

In the engineering practice of power system of electrified railway, there is a certain deviation between the power frequency angle frequency and the power frequency angle frequency. The relative deviation is as follows:

$$\delta = \frac{\omega - \omega_1}{\omega_1} \quad (8)$$

Then, it has:

$$Z_{fn} = R_{fn} + j\left[n(1+\delta)\omega_1 L - \frac{1}{n(1+\delta)\omega_1 C}\right] \quad (9)$$

Pass band width of filter:

$$PB = 2\delta_m n\omega_1 = \frac{n\omega_1}{q} \quad (10)$$

The equivalent circuit at the connection point of electric railway filter is calculated as shown in Figure 3 below.

Published by: The Mattingley Publishing Co., Inc.

TEST Engineering & Management

July - August 2020
ISSN: 0193-4120 Page No. 5563 - 5571

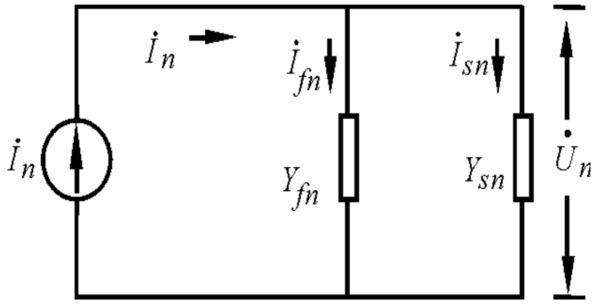

Figure 3. The equivalent circuit at the connection point of electric railway filter.

From the equivalent circuit, it can be concluded that:

$$|\dot{U}_n| = \left|\frac{\dot{I}_n}{\dot{Y}_{fn} + \dot{Y}_{sn}}\right|$$

$$= I_n\left[(G_{fn} + |\dot{Y}_{sn}|\cos\Phi_{sn})^2 + (B_{fn} - |\dot{Y}_{sn}|\sin\Phi_{sn})^2\right]^{1/2} \quad (11)$$

q_0 value is the best quality factor value of the filter after considering the influence. If the value of q_0 is used, the maximum value of $|\dot{U}_n|$ at the connection point between the filter and the grid is:

$$|\dot{U}_n|_m = \frac{4n\,\omega_1 L_1 \delta_m}{1+\cos\Phi_{sn}} I_n \quad (12)$$

In the design of single tuned filter for electrified railway, the investment of capacitor is large and easy to be damaged. Therefore, the selection of capacitor should be considered first in the design. The capacitance of capacitor in electrified railway can be determined according to the amplitude of harmonic voltage to ensure that the capacitor will not produce partial discharge during normal operation. Secondly, the harmonic capacity of electrified railway should be limited to the allowable range, so as to avoid the phenomenon of excessive dielectric loss and exceeding the allowable temperature rise.

3.2. Active power filter design

The harmonic source current is decomposed into active and reactive power, as shown in Figure 4. When the power grid U is basically a sine wave, I_p is the fundamental active current, while I_Q includes the fundamental reactive power and all harmonic currents.

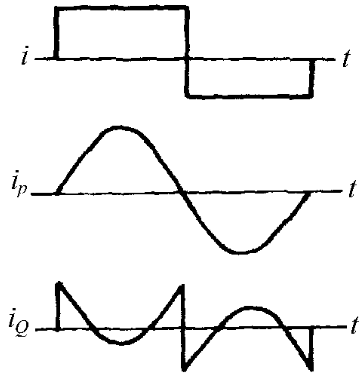

Figure 4. Time domain decomposition of current.

The main circuit of voltage type active filter is shown in Figure 5. In the DC side of the bridge, the capacitor C maintains a stable DC voltage UD, while on the AC side, the PWM voltage UD makes the output current pass through the AC reactor to compensate for the waveform distortion of the power grid. It is necessary to increase the carrier frequency when PWM is used to obtain the waveform similar to the higher harmonic, but this will be limited by the inherent switching frequency of the components used.

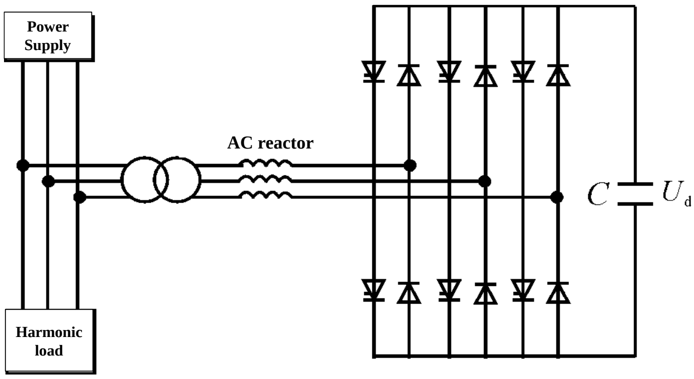

Figure 5. The main circuit of voltage type active filter.

In addition, the standard of limiting harmonic is based on the principle of limiting the harmonic current injected into the power system, controlling the harmonic content in the power system within the allowable range, so that all kinds of electrical equipment connected to the power grid are free from harmonic disturbance, and the purpose of harmonic current limit is to limit the harmonic voltage. When the limit value of voltage waveform distortion rate is

Published by: The Mattingley Publishing Co., Inc.

determined, the harmonic current is inversely proportional to the harmonic impedance of the system. The larger the short-circuit capacity of the system is, the smaller the harmonic impedance is, and the larger the allowable harmonic current is. The allowable value of harmonic current injected into the grid of the common connection point is allocated according to the ratio of the agreement capacity of the point and the power supply equipment capacity of the public connection point.

3.3. Principle of reactive power compensation

The impedance of network components in electrified railway electrical system is mainly inductive, which needs capacitive reactive power to compensate inductive reactive power. After the capacitance is incorporated into the RL circuit, the circuit is shown in figure 6. The current equation of the circuit is as follows:

$$\vec{I} = \vec{I}c + \vec{I}rl \tag{13}$$

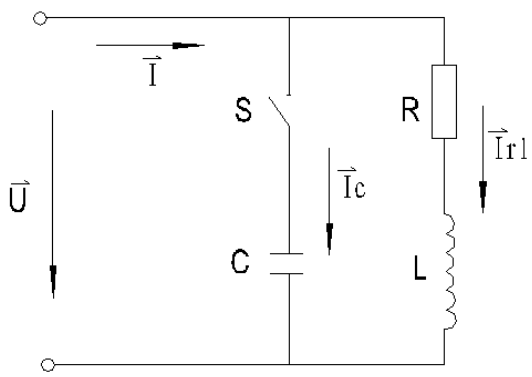

Figure 6. Capacitance incorporated into RL circuit.

After parallel connection of capacitors, the phase difference between *u* and *I* become smaller, that is to say, the power factor of power supply circuit is increased. At this time, the phase of the supply current lags behind the voltage, which is called under compensation.

3.4. Principle of reactive power compensation

If the actual operating voltage of the capacitor is inconsistent with the rated voltage of the capacitor, the actual compensation capacity of the capacitor is:

$$Q_{C1} = \left(\frac{U_W}{U_{NC}}\right)^2 Q_{NC} \tag{14}$$

In which, U_W is the actual operating voltage, U_{NC} is the rated voltage and Q_{NC} is the rated capacity.

3.5. Selection of rated voltage

The reasonable selection of rated voltage of capacitor in electrified railway should be based on the principles of avoiding grid voltage rise caused by shunt capacitor device connecting to power grid, avoiding grid voltage rise caused by harmonics, avoiding capacitor terminal voltage rise caused by installing series reactor and avoiding grid voltage rise caused by light load. Based on these principles, the rated voltage of capacitor can be calculated from the following formula:

$$U_{CN} = \frac{1.05U_{SN}}{\sqrt{3}S} \times \frac{1}{1-K} \tag{15}$$

In which, U_{CN} is the rated voltage of a single capacitor, U_{SN} is the nominal voltage of the grid at the access point of the shunt capacitor, S is the series number of each phase of the capacitor bank, and K is the reactance rate.

4. Simulation strategy of harmonic control and reactive power compensation for electrified railway

Due to the nonlinear characteristics of the locomotive load of the electrified railway, it is inevitable to produce harmonic current phenomenon and problems when it is connected to the power grid, which will bring adverse effects on the entire device and power grid of the electrified railway. In order to reduce the effect of harmonics, it is necessary to simulate and analyze the actual operation of the whole electrified railway, so as to formulate scientific and reasonable harmonics restraining and reactive compensating measures and strategies.

Published by: The Mattingley Publishing Co., Inc.

July - August 2020
ISSN: 0193-4120 Page No. 5563 - 5571

The simulation design process of the actual operation of electrified railway is as follows: firstly, the simulation system needs to have multiple harmonic filtering functions, so as to meet the harmonic limit value of power system and the allowable value of harmonic required by the standard and its test method. Secondly, in the actual operation of electric locomotive, the voltage fluctuation caused by nonlinear load needs to meet the requirements of power quality public grid harmonic standard.

In addition, the simulation of harmonic and reactive power compensation based on active power filter needs to be based on the filter group switching optimization algorithm to comprehensively consider the equipment investment, cost control and technical implementation effect of the whole scheme, so as to realize the scheme optimization within the limited investment.

5. Conclusion

At present, China's railway gradually completed the electrification transformation, electrified railway has become the focus of railway construction, and the electrified railway will face more prominent and serious harmonic and reactive power problems, these two problems will produce more serious harm to the electrified railway. This paper analyzes the application status of harmonics restraining and reactive compensating technology in electrified railway, including the influence of harmonic on electrical equipment, harmonic suppression technology and measures, as well as the role and technical status of reactive power compensation, and obtains the harmonic suppression technology and measures as well as the common ways of reactive power compensation.

In addition, through the research on the design method of harmonics restraining and reactive compensating of electrified railway, including the design of monotone and active harmonic filter and the determination of reactive power compensation principle, rated voltage and compensation mode, the optimal reactive power compensation mode is found. Finally, through the simulation research on harmonic control and reactive power compensation of electrified railway, the optimal scheme is given, which provides beneficial ideas for the development of electrified railway.

References

[1] C. F. Gu, H. Z. Ma, K. Qian, Power quality analysis of electrified railway. Journal of power system and automation, 2013, 25 (05): 133-137.

[2] T. Jiang, Y. W. Zhang, X. H. Chen, Application research of magnetic controlled reactor type dynamic reactive power compensation device in traction substation. China Railway, 2013 (2): 74-76.

[3] X. G. Liu, J. F. Zou, X. N. Sun, Simulation analysis of magnetically controlled reactor based on MATLAB. Power capacitor and reactive power compensation, 2015, 36 (1): 35-38.

[4] H. Y. Xing, B. C. Chen, Y. D. Zhang, Study on suppression of UHV switching overvoltage by fast response magnetic controlled reactor. Power automation equipment, 2019, 29 (1): 15-18.

[5] G. Wang, M. X. Tian, E. Ren, Improvement and parameter optimization of output filter with current balance compensation for electrified railway. High voltage technology, 2015 (02): 460-467.

[6] L. H. Zhou, F. Wang, X. F. Li, Research on reactive power compensation and harmonic control of multilevel power quality regulator for electrified railway. Power system protection and control, 2011 (01): 104-110.

[7] B. Yang, Research on dynamic reactive power compensation method of electrified railway. Acta electrica Sinica, 2013, 28 (2): 114-118