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Analysis of static VAr compensators installed in different positions in electric railways

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Abstract: With the power quality problems of electric railways becoming more and more serious, static VAr compensators (SVCs) have been widely used for power quality management. SVCs can be installed in the low-voltage side of traction substations, the high-voltage side of traction substations or the electric railway power supply side of substations. Different installation positions result in different compensation effects. In this study, characteristics of harmonic and negative sequence currents in the low-voltage and high-voltage sides of traction substations are analysed theoretically. Four schemes with SVCs in different installation positions are proposed. Then based on the measured datum and waveforms, simulation of each scheme is implemented, respectively, using PSCAD/EMTDC software. By comparing the compensation effects of the four schemes, the best SVC installation scheme in the low-voltage side of the traction substation is recommended for the measured traction substation. With SVC, the electric railway will have a less negative effect on the power grid. This study can also be applied to other SVC applications with non-linear loads, such as arc furnaces, rolling mills or electrochemical devices.

1 Introduction

An electric locomotive in an electric railway is a single-phase moving load with changing amplitude. Such unbalanced loads can result in negative sequence currents, harmonic currents and thus affect the power quality of power system. At present, there are many methods to solve power quality problems caused by electric railways [1–4]. Taking all the methods into account, the static VAr compensator (SVC) is thought by many to be one of the best choices. An SVC device has many merits such as proven technology, lower cost and extensive applications. It can control reactive power dynamically, improve the power factor, suppress voltage fluctuation, realise three-phase equilibrium and filter harmonics [5–7], thus making the power quality of point of common coupling (PCC) meet the national standard.

SVC has been widely used to improve electric railway power quality [8–13]. France and Britain built a three-phase SVC project together [8]; the Australian Queensland railway adopted SVC schemes in both traction substations and substations [9]; Japan used equilibrium transformers as well as SVC [10]; the Chinese Shenshuo railway adopted SVC to suppress negative sequence voltage [11, 12]; Beijing–Shanghai railway used SVC to provide voltage support [13]. An SVC used in the electric railway can be installed in the low-voltage side of a traction substation, the high-voltage side of a traction substation and the electric railway power supply side of a substation. The installation position of the SVC should be determined by the actual conditions and compensation objectives. In the Chunnel electric railway [8] and Chinese An-ding traction substation [9], single-phase SVCs were installed in the low-voltage side of the traction substation to provide voltage support and suppress harmonics, as well as to improve the power factor. To compensate for negative sequence and reactive power, North China Electric Power University proposed a kind of SVC installed in the high-voltage side of the traction substation [10]. In the Chinese Shenshuo electric railway [11, 12], an SVC was installed in the power supply side of the substation in order to compensate for the negative sequence of several traction substations in the same substation at the same time. Currently, research about different installation positions of SVCs in electric railways has not been written up in published journals. However, it is of important significance to research this issue.

In this paper, based on a theoretical analysis of harmonic and negative sequence currents in different positions, four schemes of SVCs installed in different positions are proposed, aiming at decreasing of current unbalanced degree and current harmonics of electric railways. With the measured datum and waveforms from a traction substation, simulations are implemented using PSCAD/EMTDC software. The compensation effects of SVCs in four schemes are analysed and compared. Finally, an SVC scheme that is most suitable for the measured traction substation is recommended.

2 Analysis of harmonic and negative sequence currents in electric railways

2.1 Harmonic currents in low-voltage side of traction substations

Harmonic currents in the low-voltage side of a traction substation are mainly caused by electric locomotives. Currently, electric locomotives are divided into two types: AC–DC and AC–DC–AC. A half-controlled-bridge rectifier is usually adopted in an AC–DC locomotive. It adjusts traction power by controlling thyristor firing angles. However, the power factor of an AC–DC locomotive is low. The main components of harmonic currents are odd-order currents. For example, the Chinese SS3 locomotive is of AC–DC type, in which phase-controlled thyristors and voltage-regulated switches are used to control the eight bridges [14]. The main circuit is shown in Fig. 1*a*.

An AC–DC–AC electric locomotive generally consists of a pulse-width modulation (PWM) rectifier, intermediate DC link, traction inverter and three-phase AC induction motor [15]. The

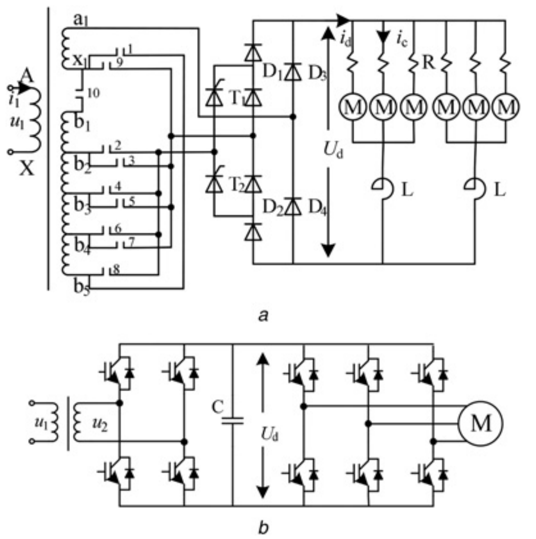

Fig. 1 *Main circuit of electric locomotives*

a Main circuit of the SS3 electric locomotive
b Main circuit of the HX_D3 electric locomotive

current waveform of a PWM four-quadrant rectifier is similar to a sine wave, and the power factor is close to 1. An example of an AC–DC–AC locomotive is the HX_D3 in China. The main circuit is shown in Fig. 1*b*. Harmonic currents in HX_D3 are generated mainly by the rectifier.

PSCAD/EMTDC software is used to analyse harmonic currents of SS3 and HX_D3 locomotives. The individual harmonic distortions (IHDs) of their currents are shown, respectively, in Figs. 2*a* and *b*. It is easy to see that the main harmonic components of an AC–DC locomotive current are the 3rd, 5th and 7th; at the same time, the amplitudes of harmonic currents decrease with an increase of harmonic order. The current of an AC–DC–AC locomotive has less low-order harmonics than that of an AC–DC locomotive, but has some high-order harmonics. The high-order harmonics are mainly distributed in times of carrier frequency. When the overhead wire of a traction substation feeds power to several locomotives, the harmonic currents of those locomotives will superimpose to constitute the total harmonic current.

2.2 Harmonic and negative sequence currents in high-voltage side of traction substations

Harmonic and negative sequence currents in the low-voltage side of traction substations have impact on the high-voltage side through traction transformers. Different traction transformers have different connection modes and ratios, resulting in different effects. At

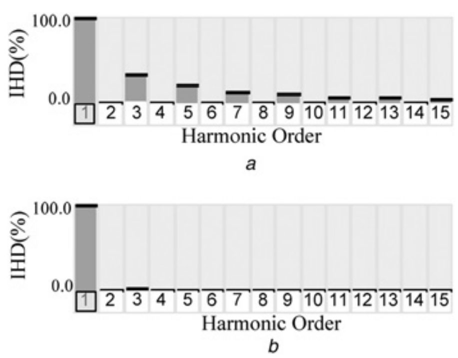

Fig. 2 *IHD of the current of locomotives*

a IHD of the current of an SS3 locomotive
b IHD of the current of an HX_D3 locomotive

present, there are five types of traction transformers in China: single-phase, V/v, Yn/d11, Scott and the impedance-matching balance transformers.

The ratio of negative sequence component root mean square (RMS) and positive sequence component RMS is called the unbalanced degree, represented by ε [16]. The current unbalanced degree ε_I is equal to the ratio of negative sequence component RMS, I_- and positive sequence component RMS, I_+. N_1 and N_2 represent winding turns of the high-voltage side and low-voltage side, respectively, the ratio of the transformer is $K = N_1/N_2$. The currents of left and right traction overhead wires are defined, respectively, as $\dot{I}_\alpha$, $\dot{I}_\beta$, the current ratio as K_I, impedance angles as α_z, β_z, and voltage angles and current angles as α_u, β_u, α_i and β_i. Their relationships can be expressed as follows

$$K_I = I_\alpha / I_\beta \tag{1}$$

$$\begin{cases} \alpha_z = \alpha_u - \alpha_i \\ \beta_z = \beta_u - \beta_i \end{cases} \tag{2}$$

Table 1 shows expressions of the three-phase currents $\dot{I}_A$, $\dot{I}_B$ and $\dot{I}_C$ in the high-voltage side, positive sequence and negative sequence currents $\dot{I}_+$, $\dot{I}_-$ and current unbalanced degree ε_I for different traction transformers [16].

From Table 1, we can see that currents of the high-voltage side are associated with traction transformer type, ratio and currents of overhead wire. In addition to the single-phase traction transformer, current unbalanced degree ε_I is not only related to the ratio of traction transformer, but also to the impedance angles of loads. When only one side of the traction overhead wires has locomotive loads, the current unbalanced degree ε_I will be the most serious.

Above all, harmonic and negative sequence currents in the low-voltage side and high-voltage side of traction substations have different features. Before using SVC, the characteristics of harmonic and negative sequence currents need to be fully considered. Then corresponding schemes and control strategy can be determined.

3 Schemes and analysis of SVC in electric railways

As a typical type of SVC, the thyristor-controlled reactor (TCR) and fixed capacitor (FC) have been widely used in metallurgy, coal and electric railways [17–19]. TCR and FC can be used to compensate for the reactive power, filter harmonics and suppress negative sequence. The role of TCR is to suppress negative sequence and decrease the current unbalanced degree. FC adopts single tuned filters that are comprised of branches of the 3rd, 5th and 7th. The role of FC is to filter harmonic currents and cooperate with the TCR dynamic regulation at the same time.

3.1 SVC schemes

Taking the voltage grade of Chinese electric railways (110 or 220 kV) as an example and considering the installed positions of TCR and FC, this paper puts forward the following schemes:

(1) *Scheme 1:* Three-phase TCR and FC are installed in the 110 kV electric railway power supply side of the substation through a step-down transformer. The connection mode is shown in Fig. 3. Since SVC cannot be connected directly to high voltages such as 110 and 220 kV, a step-down transformer is needed. However, this additional step-down transformer will increase equipment investment and decrease filter effect. Therefore this scheme is suitable in the situation that multiple traction substations are powered by the same power supply, especially when the overhead wires of the traction substation are equipped with filters.

(2) *Scheme 2:* Three-phase TCR and FC are installed in the low-voltage side of the traction transformer. The connection mode is shown in Fig. 4. This scheme is suitable for three-phase

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Table 1 Expressions of different traction transformers

Type of transformer	Currents of high-voltage side	Positive sequence and negative sequence currents	Current unbalanced degree
single-phase type	$\begin{bmatrix}\dot{I}_A\\ \dot{I}_B\\ \dot{I}_C\end{bmatrix}=\frac{1}{K}\begin{bmatrix}1 & 1\\ -1 & -1\\ 0 & 0\end{bmatrix}\begin{bmatrix}\dot{I}_\alpha\\ \dot{I}_\beta\end{bmatrix}$	$\begin{cases}\dot{I}_+=\frac{1}{3K}(1-\alpha)\left(\dot{I}_\alpha+\dot{I}_\beta\right)\\ \dot{I}_-=\frac{1}{3K}\left(1-\alpha^2\right)\left(\dot{I}_\alpha+\dot{I}_\beta\right)\end{cases}$	$e_I=1$
V/v type	$\begin{bmatrix}\dot{I}_A\\ \dot{I}_B\\ \dot{I}_C\end{bmatrix}=\frac{1}{K}\begin{bmatrix}1 & 0\\ 0 & 1\\ -1 & -1\end{bmatrix}\begin{bmatrix}\dot{I}_\alpha\\ \dot{I}_\beta\end{bmatrix}$	$\begin{cases}\dot{I}_+=\frac{1}{3}(\dot{I}_A+\alpha\dot{I}_B+\alpha^2\dot{I}_C)=\frac{1}{3K}(1-\alpha)\left[(1+\alpha)\dot{I}_\alpha+\alpha\dot{I}_\beta\right]\\ \dot{I}_-=\frac{1}{3}(\dot{I}_A+\alpha^2\dot{I}_B+\alpha\dot{I}_C)=\frac{1}{3K}(1-\alpha)(\dot{I}_\alpha-\alpha\dot{I}_\beta)\end{cases}$	$\varepsilon_I=\sqrt{\frac{K_I^2+1+2K_I\cos(\alpha_z-\beta_z-120^o)}{K_I^2+1+2K_I\cos(\alpha_z-\beta_z)}}\times 100\%$
Yn/d11 type	$\begin{bmatrix}\dot{I}_A\\ \dot{I}_B\\ \dot{I}_C\end{bmatrix}=\frac{\sqrt{3}}{K}\begin{bmatrix}-2 & -1\\ 1 & -1\\ 1 & 2\end{bmatrix}\begin{bmatrix}\dot{I}_\alpha\\ \dot{I}_\beta\end{bmatrix}$	$\begin{cases}\dot{I}_+=\frac{1}{3}\left(\dot{I}_A+\alpha\dot{I}_B+\alpha^2\dot{I}_C\right)=\frac{\sqrt{3}}{3K}\left(-\dot{I}_\alpha+\alpha^2\dot{I}_\beta\right)\\ \dot{I}_-=\frac{1}{3}\left(\dot{I}_A+\alpha^2\dot{I}_B+\alpha\dot{I}_C\right)=\frac{\sqrt{3}}{3K}\left(-\dot{I}_\alpha+\alpha\dot{I}_\beta\right)\end{cases}$	$\varepsilon_I=\sqrt{\frac{K_I^2+1+2K_I\cos(\alpha_z-\beta_z-120^o)}{K_I^2+1+2K_I\cos(\alpha_z-\beta_z)}}\times 100\%$
scott type	$\begin{bmatrix}\dot{I}_A\\ \dot{I}_B\\ \dot{I}_C\end{bmatrix}=\frac{1}{\sqrt{3}K}\begin{bmatrix}2 & 0\\ -1 & \sqrt{3}\\ -1 & -\sqrt{3}\end{bmatrix}\begin{bmatrix}\dot{I}_\alpha\\ \dot{I}_\beta\end{bmatrix}$	$\begin{cases}\dot{I}_+=\frac{1}{3}\left(\dot{I}_A+\alpha\dot{I}_B+\alpha^2\dot{I}_C\right)=\frac{1}{\sqrt{3}K}\left(\dot{I}_\alpha+\dot{I}_\beta e^{-j90^o}\right)\\ \dot{I}_-=\frac{1}{3}\left(\dot{I}_A+\alpha^2\dot{I}_B+\alpha\dot{I}_C\right)=\frac{1}{\sqrt{3}K}\left(\dot{I}_\alpha+\dot{I}_\beta e^{-j90^o}\right)\end{cases}$	$\varepsilon_I=\sqrt{\frac{K_I^2+1-2K_I\cos(\alpha_z-\beta_z)}{K_I^2+1+2K_I\cos(\alpha_z-\beta_z)}}\times 100\%$
impedance-matching balanced type	$\begin{bmatrix}\dot{I}_A\\ \dot{I}_B\\ \dot{I}_C\end{bmatrix}=\frac{1}{2\sqrt{3}K}\cdot\begin{bmatrix}\sqrt{3}+1 & -\sqrt{3}+1 & 2\sqrt{3}K_0\\ -2 & -2 & 2\sqrt{3}K_0\\ -\sqrt{3}+1 & \sqrt{3}+1 & 2\sqrt{3}K_0\end{bmatrix}\begin{bmatrix}\dot{I}_\alpha\\ \dot{I}_\beta\\ \dot{I}_0\end{bmatrix}$	$\begin{cases}\dot{I}_+=\frac{1}{4\sqrt{3}K}\{[(\sqrt{3}+1)-j(\sqrt{3}-1)]\dot{I}_\alpha\\ +[(\sqrt{3}+1)-j(\sqrt{3}-1)]\dot{I}_\beta\}\\ \dot{I}_-=\frac{1}{4\sqrt{3}K}\{[(\sqrt{3}+1)+j(\sqrt{3}-1)]\dot{I}_\alpha\\ +[-(\sqrt{3}+1)-j(\sqrt{3}-1)]\dot{I}_\beta\}\end{cases}$	$\varepsilon_I=\sqrt{\frac{K_I^2+1-2K_I\cos(\alpha_z-\beta_z)}{K_I^2+1+2K_I\cos(\alpha_z-\beta_z)}}\times 100\%$

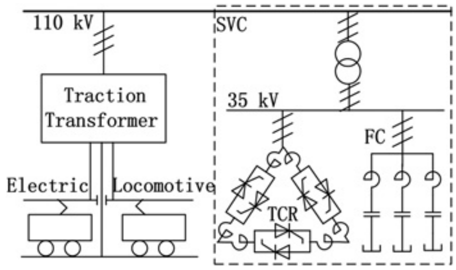

Fig. 3 *Connection mode of Scheme 1*

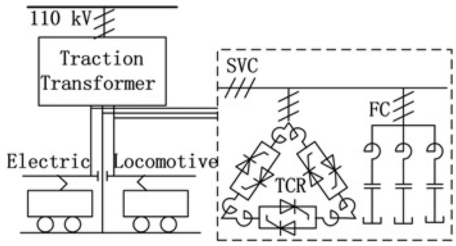

Fig. 4 *Connection mode of Scheme 2*

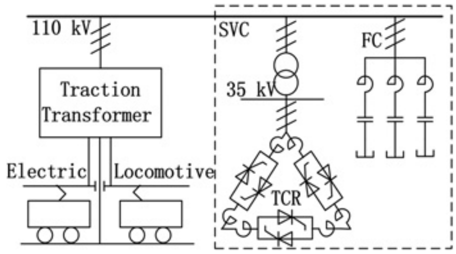

Fig. 5 *Connection mode of Scheme 3*

transformers, such as V/v, Yn/d11 and balance types. In practice, in order to avoid a serious unbalance in PCC, traction substations that are powered by the same substation are connected to the PCC in a transposition manner. Therefore in Scheme 2, the total SVC capacity of every single traction substation connected to PCC is potentially larger than that of Scheme 1, which means the corresponding cost is potentially more than that of Scheme 1.

(3) *Scheme 3:* Three-phase TCR are installed in the high-voltage side of the traction transformer through a step-down transformer. An FC is installed directly on the 110 kV (or 220 kV) side, which can reduce the influence of the step-down transformer on harmonic filtering. A connection mode is shown in Fig. 5.

(4) *Scheme 4:* A single-phase TCR and FC are installed in the low-voltage side of the traction transformer. Connection mode is shown in Fig. 6. This scheme aims to suppress voltage fluctuation, as well as adjust reactive power and reduce the influence of negative sequence.

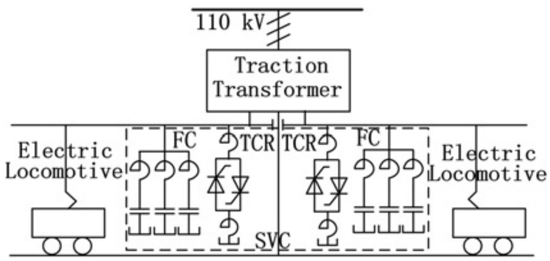

Fig. 6 *Connection mode of Scheme 4*

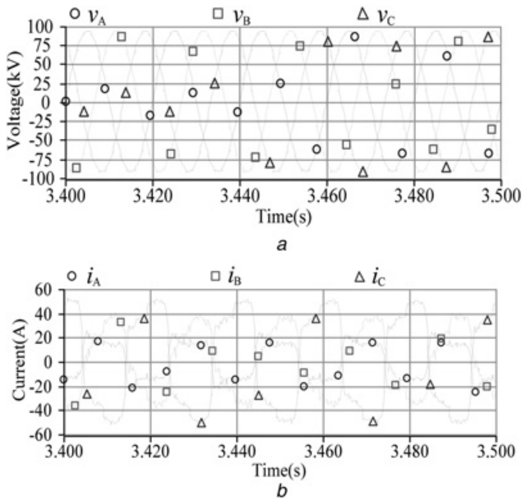

Fig. 7 *Measured waveforms*

a Measured voltage waveforms
b Measured current waveforms

3.2 Comparative analysis of SVC schemes

On the basis of the datum and waveforms from a measured traction substation in the South-West area of China, four schemes are simulated and analysed in PSCAD/EMTDC software.

The measured data here are from a Chinese traction substation. Two 110/27.5 kV traction transformers with Yn/d11 connection are installed in this traction substation. One is in service and the other is on stand-by. The capability of the transformer is 2 × 12.5 MVA. Most freight train locomotives are HX_D3, whereas most passenger train locomotives are SS3. Data are measured by an American Dranetz-BMI PowerVisa power quality analyser. The measured position is the 110 kV high-voltage side of the traction substation. Actual voltage and current waveforms are shown in Figs. 7*a* and *b*.

The measured total harmonic distortions (THDs) of voltage THD_U and current THD_I in the system side are shown in Table 2. The current unbalanced degree ε_I is 72.25%.

Obviously, the voltage waveform has few harmonics; the THDs of voltage THD_U are within the prescribed range of the corresponding Chinese power quality standard. However, the current waveforms contain a large number of harmonics. The measured THDs and unbalance degree of currents are very serious. Therefore SVC is needed to improve the power quality, especially decreasing of current unbalanced degree and current harmonics.

In this paper, the control strategies for four schemes are different. For schemes 1–3, based on the balancing principle of unbalanced loads (Steinmetz principle) [20–22], the PSCAD/EMTDC software is used to build circuits for detecting negative sequence components as well as generating three-phase compensative currents. The control strategy of single-phase TCR in Scheme 4 is voltage negative feedback with reactive power compensation.

(1) *Scheme 1:* On the basis of the datum from measured traction substation, simulation of Scheme 1 is implemented. The rated capacity of TCR is 32 MVar and the total rated capacity of FC is 16 MVar. Three-phase currents of the high-voltage side of the traction transformer are shown in Fig. 8.

Table 2 Measured THD

	Phase A	Phase B	Phase C
THD_I, %	48.49	19.76	30.68
THD_U, %	0.41	0.38	0.71

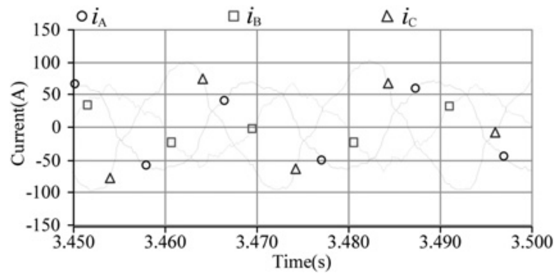

Fig. 8 *Current waveforms of Scheme 1*

Table 3 THD of Scheme 1

	Phase A	Phase B	Phase C
THD_I, %	12.09	14.03	14.41
THD_U, %	0.41	0.45	0.6

The current positive sequence component is $0.08618\angle -74.1°$ kA; the negative sequence component is $0.01606\angle 200.5°$ kA. Therefore the current unbalanced degree ε_I is 18.63%. The THDs of both voltages and currents in the system side are shown in Table 3.

From Fig. 8 and Table 3, we can see that THDs of both voltage and current are reduced, harmonic currents are decreased and current unbalanced degree is decreased from 72.25 to 18.63%.

(2) *Scheme 2:* On the basis of the datum from the measured traction substation, the simulation of Scheme 2 is implemented. The rated capacity of TCR is 16 MVar and the total rated capacity of FC is 16 MVar. Three-phase currents of the high-voltage side of the traction transformer are shown in Fig. 9.

The current positive sequence component is $0.04842\angle -62°$ kA; the negative sequence component is $0.01577\angle 221.2°$ kA. Therefore the current unbalanced degree ε_I is 32.56%. The THDs of both voltages and currents in the system side are shown in Table 4.

From Fig. 9 and Table 4, we can see that both voltage and current THDs are reduced, harmonic currents are decreased and current unbalanced degree is decreased to 32.56%.

(3) *Scheme 3:* On the basis of the datum from the measured traction substation, the simulation of Scheme 3 is implemented. The rated capacity of TCR is 32 MVar and the total rated capacity of FC is 16 MVar. Three-phase currents of the high-voltage side of the traction transformer are shown in Fig. 10.

The current positive sequence component is $0.06786\angle -69.7°$ kA; the negative sequence component is $0.01672\angle 199.4°$ kA. Therefore

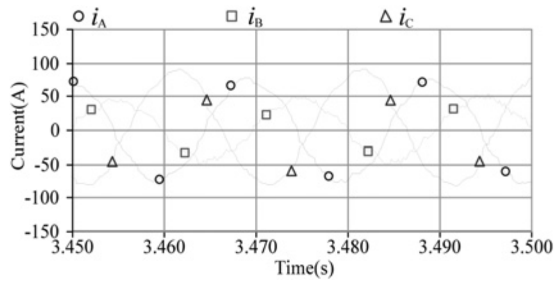

Fig. 9 *Current waveforms of Scheme 2*

Table 4 THD of Scheme 2

	Phase A	Phase B	Phase C
THD_I, %	7.68	8.52	6.33
THD_U, %	0.32	0.35	0.35

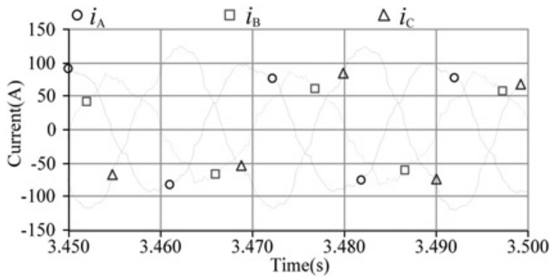

Fig. 10 *Current waveforms of Scheme 3*

Table 5 THD of Scheme 3

	Phase A	Phase B	Phase C
THD_I, %	8.15	10.99	8.94
THD_U, %	0.44	0.59	0.55

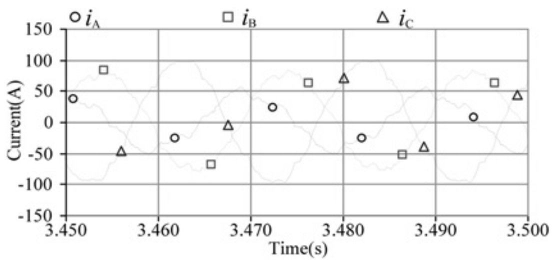

Fig. 11 *Current waveforms of Scheme 4*

Table 6 THD of Scheme 4

	Phase A	Phase B	Phase C
THD_I, %	17.66	7.68	5.9
THD_U, %	0.45	0.48	0.43

the current unbalanced degree ε_I is 24.64%. The THDs of both voltages and currents in the system side are shown in Table 5.

From Fig. 10 and Table 5, we can see that both voltage and current THD are reduced, harmonic currents are decreased and current unbalanced degree is decreased to 24.64%.

(4) *Scheme 4*: On the basis of the datum from the measured traction substation, the simulation of Scheme 4 is implemented. The total rated capacity of TCR is 16 MVar and the total rated capacity of FC is 16 MVar. Three-phase currents of the high-voltage side of the traction transformer are shown in Fig. 11.

The current positive sequence component is $0.05026\angle -63.6°$ kA; the negative sequence component is $0.02165\angle 142.3°$ kA. Therefore the current unbalanced degree ε_I is 43.07%. The THDs of both voltages and currents in the system side are shown in Table 6.

From Fig. 11 and Table 6, we can see that THD of both voltage and current are reduced, harmonic currents are decreased and current unbalanced degree is decreased to 43.07%. However, the compensated effect of the negative sequence is not better than the other three schemes.

3.3 *Recommended scheme*

THDs and unbalanced degrees of these four schemes are listed in Table 7 for the convenience of analysing.

Comparing the datum in Table 7, it is easy to find that both THDs of voltage and current are reduced after using SVC. Negative sequence unbalanced degrees are decreased and power quality is improved. Therefore the four schemes are successful. Considering only THDs and unbalanced degrees of current, the compensation effects of Schemes 1 and 2 are better than the other two schemes. Scheme 1 is better in balancing the negative sequence with the current unbalanced degree of 18.63%. Scheme 2 has a better effect on filtering harmonic currents. On the one hand, FC in Scheme 2 is connected to the low-voltage grade without using a step-down transformer, insulation requirement and transformer cost are reduced. And the voltage loss caused by the traction transformer is avoided when SVC is installed in the low-voltage side of the traction substation. Voltage loss of the traction network is more conducive to compensate. All in all, the results verify that Scheme 2 is the most effective and feasible method to improve power quality, considering safety and cost. Scheme 2 in which SVC is installed in the low-voltage side of the traction substation is the most suitable solution for the measured traction substation.

4 Conclusion

Harmonic and negative sequence components in the power system of electric railways can be compensated using SVC. In this paper, characteristics of harmonic and negative sequence currents in different positions were analysed. Four SVC schemes based on different installed positions and compensation objectives have been proposed, and simulated with measured datum. Through analysis and comparison, power quality can be improved when an SVC device is installed in the low-voltage side of a traction substation for the measured traction substation. When the three-phase SVC is installed in the low-voltage side of a traction transformer, voltage loss caused by a traction transformer can be avoided. The merits in safety and cost are prominent. This paper can also be suitable for other applications of SVC in non-linear loads system, such as arc furnaces, rolling mills and electrochemical devices. For example, SVC can also be installed in different positions in arc furnaces to improve power quality. It

Table 7 Comparison of four schemes

	Without SVC			Scheme 1		
	A	B	C	A	B	C
THD_I, %	48.84	22.69	31.64	12.1	14.03	14.41
THD_U, %	0.405	0.426	0.723	0.41	0.45	0.6
ε_I, %		72.25			18.63	

	Scheme 2			Scheme 3			Scheme 4		
	A	B	C	A	B	C	A	B	C
THD_I, %	7.68	8.52	6.33	8.15	10.99	8.94	17.55	7.68	5.9
THD_U, %	0.32	0.35	0.35	0.44	0.59	0.55	0.45	0.48	0.43
ε_I, %		32.56			24.64			43.07	

is of vital importance to analyse and compare the effects of SVC installed in different positions, so as to find the most suitable scheme.

5 Acknowledgments

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