9

Power Quality Issues in Traction Power Systems

There are serious power quality issues in traction power systems, including negative-sequence currents, current harmonics and low power factor, in addition to voltage harmonics. In this chapter, these issues are dealt with. A topology for traction power systems with a single feeding wire is implemented with a three-phase V/V transformer and a three-phase converter. Compared to the traditional scheme with two feeding wires (in two phases) with three-phase V/V transformers, this topology improves the system reliability and has the potential for the traction of high-speed trains. Compared to the co-phase system proposed in the literature, this topology adopts a simple normal transformer instead of a complicated YNvd transformer and a three-phase converter instead of a back-to-back single-phase converter, which saves one converter leg. A strategy is then presented to control the three-phase converter so that all harmonic, negative-sequence and reactive currents generated by the non-linear single-phase load of locomotives are compensated. As a result, only balanced real power is drawn from the grid. Simulation results are provided to illustrate the performance of the system.

9.1 Introduction

In recent years, high-speed electrified trains have been rapidly developed all over the world and this is the future trend for railway transport. But for traditional traction power systems, there are some power quality problems such as low power factor, a significant amount of harmonics and negative-sequence currents caused by locomotives, which are present as single-phase non-linear loads (Chen *et al.* 1998). As a result, the grid currents are unbalanced and contain a lot of harmonics and reactive power (Chang *et al.* 2004; Ledwich and George 1994; Lee *et al.* 2006; Tan *et al.* 2003).

The problem of reactive power and harmonics is partially solved nowadays because high-speed locomotives are driven by four-quadrant PWM converters (Brenna *et al.* 2011; Busco *et al.* 2003; Chen *et al.* 2004). However, the problem with negative-sequence currents becomes more and more serious because the power of locomotives is increasing. An overview

Control of Power Inverters in Renewable Energy and Smart Grid Integration, First Edition.
Qing-Chang Zhong and Tomas Hornik.

of the imbalance in traction power systems is presented in (Kneschke 1985) and the unbalanced currents in different kinds of power supply schemes are compared. The amount of negative-sequence currents are determined by the topology of the traction power system, especially the type of transformers adopted, and the power of locomotives. In traditional traction power systems, the topology with two-phase feeding wires is widely used (Chen *et al.* 2004). There are two main schemes in this category according to the transformers used: (i) with three-phase V/V transformers; and (ii) with some balancing transformers such as Scott transformers (Horita *et al.* 2010; Ming-Li *et al.* 2008), Woodbridge transformers (Morimoto *et al.* 2009) and Le Blanc transformers (Huang and Chen 2002). The detailed evaluation of negative-sequence currents injected into the grid from different traction substations equipped with different transformers is given in (Chen and Guo 1996; Wang *et al.* 2009). If a balancing transformer is used, the two-phase secondary currents result in balanced three phase currents on the grid side under some specific load conditions. However, since the speed and load of locomotives change frequently, the grid currents are normally unbalanced. In order to solve this problem, some active power compensators (APC) can be adopted on the three-phase grid side or on the two-phase track side. For example, an APC was proposed in (Sun *et al.* 2004) for a traction power system equipped with a Scott transformer to compensate for the negative-sequence currents.

Compared to balancing transformers, three-phase V/V transformers have a simple structure. However, since the V/V connection scheme is inherently unbalanced, its performance in reducing the three-phase imbalance is essentially worse than that of balancing transformers. In order to deal with this problem, a three-phase V/V transformer with a railway static power conditioner (RPC) is proposed in (Luo *et al.* 2011) and a strategy to compensate the negative-sequence and harmonic currents is explained. Some improved strategies are then proposed in (Wu *et al.* 2012), where a three-phase converter is used to replace the single-phase back-to-back converter.

In comparison with the traditional two-phase systems, the topology with a single feeding wire has some obvious advantages. First of all, the neutral section needed for each substation to separate the two phases can be removed. Secondly, the voltages on the two adjacent sections are nearly of the same phase so the insulation requirement between two adjacent sections is considerably reduced and the neutral sections needed by two-phase systems can be replaced with section insulators. Thirdly, the insulation/neutral sections for two-phase systems are quite long and the speed loss of locomotives when passing through neutral sections is quite significant. Compared to two-phase schemes, the number and length of neutral sections in single-feeder systems are considerably reduced. Therefore, the topology with a single feeding wire is more appropriate to provide power to high-speed trains.

Systems with a single feeding wire are explored in the literature. Such a system can be achieved by using a Steinmetz transformer (Driesen and Craenenbroeck 2002), which is a three-phase transformer with an extra power balancing load composed of a capacitor and an inductor rated proportional to the single-phase load. An obvious drawback is that the capacitor and the inductor need to be changed when the load changes. As a result, the capacitor and inductor can be replaced with static var compensators (SVC) (ABB 2010). A co-phase power traction system is proposed in (Shu *et al.* 2011; Zhao *et al.* 2010), where a complicated YNvd balancing transformer and an APC are used. After compensation, only the active power, including the load active power and system losses, is provided by the grid and in a balanced manner. All the active power is provided through the YNvd transformer and half of it flows through the APC. Some further optimised design and performance evaluation of the co-phase system are reported in (Chen *et al.* 2009).

Compared with the three-phase V/V scheme in (Luo *et al.* 2011), the YNvd transformer in the co-phase system is much more complicated than the single-phase transformers connected in the three-phase V/V scheme. Moreover, the APC adopted in the co-phase system is a single-phase back-to-back converter, which requires one more converter leg than the three converter legs needed by the three-phase V/V scheme.

In order to combine the advantages of the co-phase system and the three-phase V/V scheme, a new topology for traction power systems is presented in this chapter. It adopts a three-phase V/V transformer and a three-phase converter running as a static power conditioner (SPC). Moreover, it provides a single feeding wire without the need for a neutral section at each substation. The three-phase SPC is controlled to balance the three-phase grid currents and to compensate for the reactive and harmonic currents. The case when the power factor of the load is not unity is discussed in detail and the case with a unity power factor is presented as a special case. The harmonic components are compensated without any extra cost. A compensation strategy is presented so that all the harmonics and reactive power caused by the load are injected into the SPC. Hence, the grid currents are balanced and in phase with the corresponding phase voltages. It is worth noting that the SPC also maintains the DC-bus voltage and there is no need for an external power supply. The ripple voltage at the double frequency in the controller maintaining the DC-bus voltage is removed to make sure that the reference currents generated for the SPC are purely sinusoidal, which improves the THD of the grid currents.

9.2 Description of the Topology

The topology for traction power systems with a single feeding wire is shown in Figure 9.1. It adopts a three-phase V/V transformer to reduce the grid-side three-phase high voltage, e.g. 220 kV, to the track-side voltage, e.g. 27.5 kV, for traction. The turns ratio of the transformer is K_V. One open end of the secondary V windings, Terminal b in Figure 9.1, is connected to the track (earth) and the other open end of the secondary V windings, Terminal a in Figure 9.1, is connected to the catenary. A three-phase converter (called the static power conditioner, SPC) is connected to the two open ends of the secondary V windings and the common point, via two step-down single-phase transformers with a turns ratio of K_D in Figure 9.1. The SPC maintains the DC-bus voltage by itself and there is no need to provide an external power supply. The leakage inductances of the step-down transformers on the SPC side are denoted as L_a and L_b, respectively. Since the traction voltage is the grid line voltage divided by K_V, which is the same as the one in the conventional two-phase systems equipped with V/V transformers, an SPC can be easily retrofitted into existing two-phase traction power systems to improve power quality.

9.3 Compensation of Negative-sequence Currents, Reactive Power and Harmonic Currents

9.3.1 Grid-side Currents before Compensation

Assume the RMS value of the grid voltage is U and the phase angle of Phase A grid voltage is 0. Then the three phase grid voltages can be denoted as

$$\begin{cases} \dot{U}_A = U\angle 0, \\ \dot{U}_B = U\angle -\frac{2}{3}\pi, \\ \dot{U}_C = U\angle \frac{2}{3}\pi. \end{cases} \tag{9.1}$$

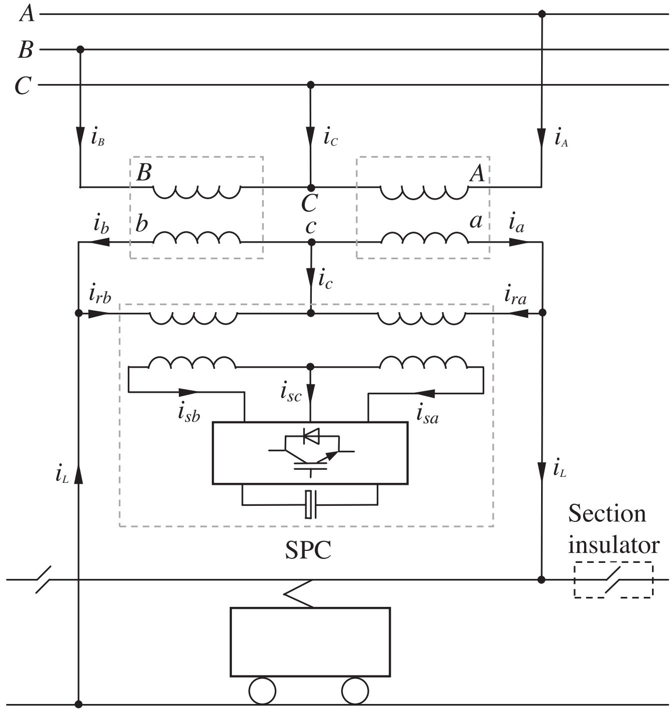


Figure 9.1 Traction power system with a single feeding wire equipped with a V/V transformer

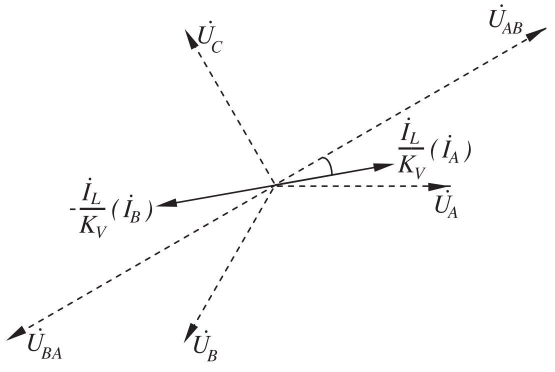
The load current i_L is assumed to be purely sinusoidal without any harmonics for the moment (the case with harmonic currents will be discussed later) and the power factor is $\cos\theta$. Then, the load current can be expressed as

$$\dot{I}_L = I_{L1}\angle\left(\frac{\pi}{6} - \theta\right) \tag{9.2}$$

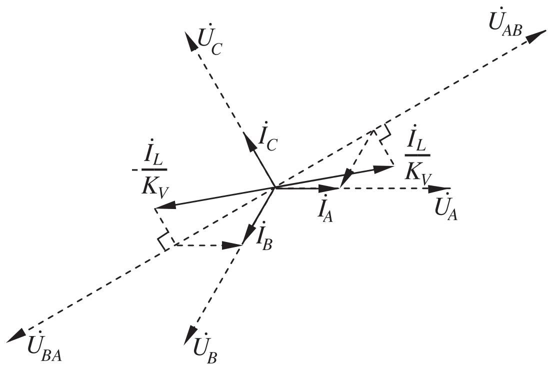
where I_{L1} is the RMS value of the fundamental load current. The three-phase grid currents without any compensation are

$$\begin{cases} \dot{I}_A = \dfrac{I_{L1}}{K_V}\angle\left(\dfrac{\pi}{6} - \theta\right), \\ \dot{I}_B = \dfrac{I_{L1}}{K_V}\angle\left(-\dfrac{5}{6}\pi - \theta\right), \\ \dot{I}_C = 0, \end{cases} \tag{9.3}$$

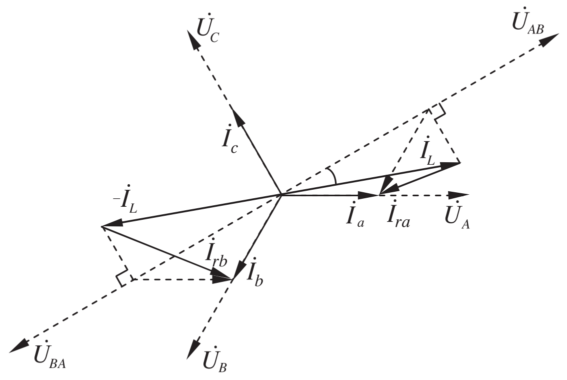
as shown in Figure 9.2(a). It is obvious that the three-phase grid currents are unbalanced. Both reactive and active current components are included in $\dot{I}_A$ and $\dot{I}_B$ as they are not in phase with $\dot{U}_A$ and $\dot{U}_B$, respectively. Phase-A current leads its voltage by $\frac{\pi}{6} - \theta$ and Phase-B current leads its voltage by $-\frac{\pi}{6} - \theta$. A significant amount of negative-sequence currents exists in the grid currents.



(a) At the grid side before compensation



(b) At the grid side after compensation



(c) At the track side after compensation

Figure 9.2 Phasor diagram of the system

9.3.2 Compensation of Active and Reactive Power

In order to make the three-phase currents balanced and obtain the unity power factor at the grid side, all the reactive power consumed by the load should be provided by the SPC. Since there is no external power supply to maintain the DC-bus voltage of the SPC, the active power consumed by the SPC should be zero when the losses are ignored. In this case, the active power consumed by the load, i.e., $\sqrt{3}U \times \frac{I_{L1}}{K_V}\cos\theta$, should be provided by the grid currents in a balanced way. Hence, the RMS value of the three-phase grid currents after compensation should be

$$\frac{\sqrt{3}U\dfrac{I_{L1}}{K_V}\cos\theta}{3U} = \frac{I_{L1}\cos\theta}{\sqrt{3}K_V},$$

which means the three-phase grid currents should be

$$\begin{cases} \dot{I}_A = \dfrac{I_{L1}\cos\theta}{\sqrt{3}K_V}\angle 0, \\ \dot{I}_B = \dfrac{I_{L1}\cos\theta}{\sqrt{3}K_V}\angle -\dfrac{2}{3}\pi, \\ \dot{I}_C = \dfrac{I_{L1}\cos\theta}{\sqrt{3}K_V}\angle\dfrac{2}{3}\pi. \end{cases} \tag{9.4}$$

The corresponding phasor diagram is shown in Figure 9.2(b). Mapping the grid-side currents to the track side, the corresponding three-phase currents are

$$\begin{cases} \dot{I}_a = \dfrac{I_{L1}\cos\theta}{\sqrt{3}}\angle 0, \\ \dot{I}_b = \dfrac{I_{L1}\cos\theta}{\sqrt{3}}\angle -\dfrac{2}{3}\pi, \\ \dot{I}_c = \dfrac{I_{L1}\cos\theta}{\sqrt{3}}\angle\dfrac{2}{3}\pi. \end{cases} \tag{9.5}$$

Therefore, the Phase-A and Phase-B compensation currents provided by the three-phase converter are

$$\begin{cases} \dot{I}_{ra} = \dot{I}_a - \dot{I}_L, \\ \dot{I}_{rb} = \dot{I}_b + \dot{I}_L. \end{cases}$$

or

$$\begin{cases} i_{ra} = i_a - i_L, \\ i_{rb} = i_b + i_L. \end{cases} \tag{9.6}$$

The Phase-C compensation current is

$$i_{rc} = i_c = -i_{ra} - i_{rb}.$$

The phasor diagram of the system at the track side after compensation is shown in Figure 9.2(c). It can be seen that I_{ra} and I_{rb} are not the same unless $\cos\theta = 1$. Because of the high voltage of the traction power system, two single-phase step-down transformers with turns ratio of K_D can be used.

It is worth noting that, after compensation, the loss in the grid transmission line is reduced by

$$1 - \frac{3 \times \left(\frac{I_{L1}\cos\theta}{\sqrt{3}K_V}\right)^2}{2 \times \left(\frac{I_{L1}}{K_V}\right)^2} = 1 - \frac{\cos^2\theta}{2}.$$

That is, the loss is reduced by at least 50%.

9.3.3 Compensation of Harmonic Currents

The above analysis is based on the assumption that there is no harmonics in the load current. As a matter of fact, according to (9.6), all the harmonic current components, if any, are automatically diverted into the compensation currents i_{ra} and i_{rb} since i_a and i_b only contain the fundamental current component. Therefore, no extra effort is needed to suppress the harmonics. It is worth noting that the current i_{rc} (i_c) only contains fundamental components even if the load current contains harmonics.

9.3.4 Regulation of the DC-bus Voltage

A stable DC-link voltage is required in order for the SPC to work properly. This can be achieved by introducing a PI controller to maintain the DC bus voltage V_c at the DC-bus reference voltage V_{cref}. The output of the DC-bus voltage controller is added on to the required RMS value of the track-side currents so that the right amount of active power can be injected into the SPC. Because of the double frequency ripple component in the DC-bus voltage, a low-pass filter, such as the hold filter

$$H(s) = \frac{1 - e^{-Ts/2}}{Ts/2},$$

where T is the fundamental period of the system, can be adopted to measure the DC component of V_c for feedback.

9.3.5 Implementation of the Compensation Strategy

The above compensation strategy can be implemented as shown in Figure 9.3. The sinusoidal tracking algorithm (STA) (Ziarani and Konrad 2004) (see also Chapter 22) is adopted to calculate the phase of the fundamental component of the grid line voltage u_{ab}. The phase of the voltage u_{ab} is $\omega t + \frac{\pi}{6}$ so it can be used to generate the signal $\sin(\omega t)$ and $\sin(\omega t - \frac{2\pi}{3})$ needed to form the reference compensation currents. The product of $\sin(\omega t + \frac{\pi}{6})$ with the fundamental load current is

$$\begin{aligned}
&\sin\left(\omega t + \frac{\pi}{6}\right) \times \sqrt{2}I_{L1}\sin\left(\omega t + \frac{\pi}{6} - \theta\right) \\
&= \frac{\sqrt{2}I_{L1}}{2}\left(\cos\theta - \cos\left(2\omega t + \frac{\pi}{3} - \theta\right)\right),
\end{aligned}$$

of which the DC component $\frac{\sqrt{2}}{2}I_{L1}\cos\theta$ can be multiplied with $\frac{2}{\sqrt{3}}$ to obtain the required amplitude of the track-side currents, i.e., $\sqrt{2} \times \frac{1}{\sqrt{3}}I_{L1}\cos\theta$.

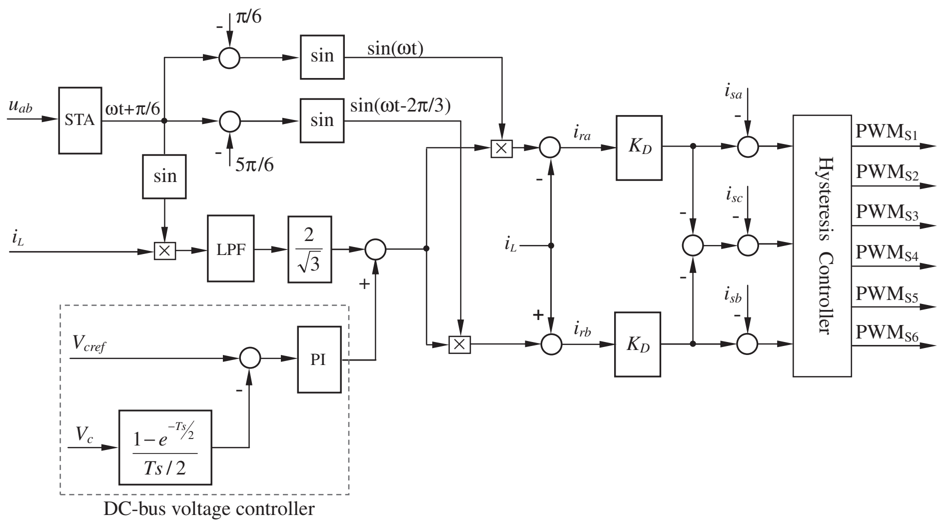


Figure 9.3 Control strategy to compensate negative-sequence, reactive and harmonic currents

The major control problem is for the SPC to track the calculated reference compensation currents i_{ra}, i_{rb} and i_{rc}. This can be done with many control strategies. For example, the repetitive controller discussed in other chapters is a very good candidate that works with a fixed switching frequency. In this chapter, three hysteresis controllers are adopted to generate PWM signals to drive the converter switches, as shown in Figure 9.3.

9.4 Special Case: $\cos\theta = 1$

Nowadays, many high-speed trains are equipped with four-quadrant converters and the power factor of the load is nearly 1. In this case, the load current is

$$\dot{I}_L = I_{L1}\angle\frac{\pi}{6}$$

and the grid currents before compensation are

$$\begin{cases} \dot{I}_A = \dfrac{I_{L1}}{K_V}\angle\dfrac{\pi}{6}, \\ \dot{I}_B = \dfrac{I_{L1}}{K_V}\angle-\dfrac{5}{6}\pi, \\ \dot{I}_C = 0. \end{cases}$$

After compensation, the grid currents are

$$\begin{cases} \dot{I}_A = \dfrac{I_{L1}}{\sqrt{3}K_V}\angle 0, \\ \dot{I}_B = \dfrac{I_{L1}}{\sqrt{3}K_V}\angle-\dfrac{2}{3}\pi, \\ \dot{I}_C = \dfrac{I_{L1}}{\sqrt{3}K_V}\angle\dfrac{2}{3}\pi. \end{cases}$$

and the three-phase currents on the track side are

$$\begin{cases} \dot{I}_a = \dfrac{I_{L1}}{\sqrt{3}}\angle 0, \\ \dot{I}_b = \dfrac{I_{L1}}{\sqrt{3}}\angle -\dfrac{2}{3}\pi, \\ \dot{I}_c = \dfrac{I_{L1}}{\sqrt{3}}\angle \dfrac{2}{3}\pi. \end{cases} \tag{9.7}$$

The corresponding phasor diagrams are shown in Figure 9.4. In this case, the compensation currents

$$\begin{cases} \dot{I}_{ra} = \dfrac{I_{L1}}{\sqrt{3}}\angle -\dfrac{2}{3}\pi, \\ \dot{I}_{rb} = \dfrac{I_{L1}}{\sqrt{3}}\angle 0, \\ \dot{I}_{rc} = \dfrac{I_{L1}}{\sqrt{3}}\angle \dfrac{2}{3}\pi, \end{cases} \tag{9.8}$$

are balanced but in the negative sequence, with the same amplitude as that of the currents on the secondary side of the V/V transformer.

9.5 Simulation Results

Simulations were carried out in MATLAB®/Simulink® to verify the strategy. The solver used was ode23tb with a maximum step size of 1 μs.

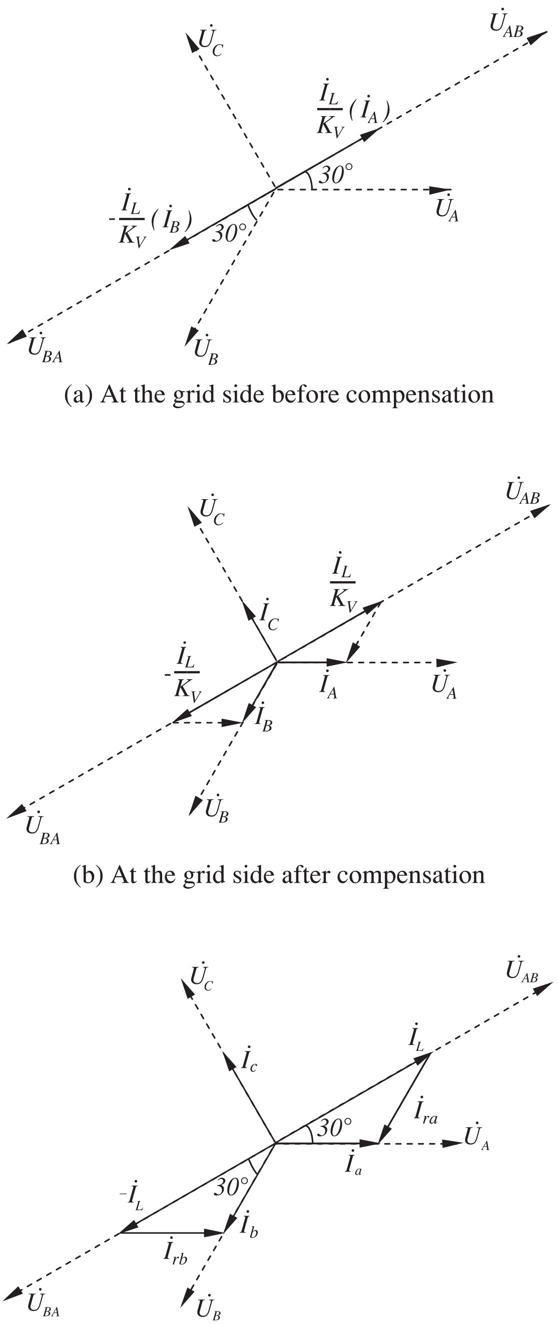
The model of the high-speed train is shown in Figure 9.5. The turns ratio of the locomotive transformer is 27.5:1.5 and the parameters are: $R_1 = 0.5\ \Omega$, $L_1 = 1.5$ mH, $C_1 = 1000\ \mu$F, $R = 6\ \Omega$, $L = 20$ mH and $C = 460\ \mu$F. The capacitor C_1 is chosen as 1000 μF to obtain a power factor of 0.6. The parameters of the PI controller for the DC-bus voltage are $K_p = 0.1$ and $K_i = 0.005$. The parameters of the traction power system are given in Table 9.1.

9.5.1 *The Case when* $\cos\theta \neq 1$

The THD of the load current was 30%. The system was started at 0 s and the SPC was turned on at 0.08 s. The load current is shown in Figure 9.6(a) and the three-phase grid-side currents are shown in Figure 9.6(b). It can be seen that the Phase-C current before compensation is 0. In addition, there is a significant amount of harmonics in i_A and i_B. After compensation, the three-phase grid currents are balanced and clean. Moreover, the amplitude of the grid currents is reduced considerably. As shown in Figure 9.6(c), the DC-bus voltage was initially set at 4600 V and was maintained close to the reference voltage after the SPC was turned on. The compensation currents generated by the three-phase converter are shown in Figure 9.6(d). The THD of Phase-A current at the grid-side dropped from 30% to 1%, as shown in Figure 9.6(e) and its zoomed version in Figure 9.6(f).

9.5.2 *The Case when* $\cos\theta = 1$

In this case, the train model is changed to a purely resistive load of 5 Ω connected to the locomotive transformer. The corresponding curves are shown in Figure 9.7 when the SPC was turned on at 0.08 s. Similar performance was obtained.



(a) At the grid side before compensation

(b) At the grid side after compensation

(c) At the track side after compensation

Figure 9.4 Phasor diagrams of the system when $\cos\theta = 1$

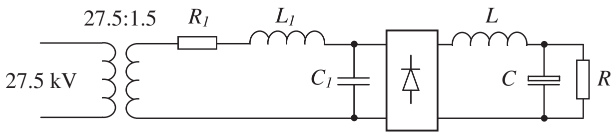
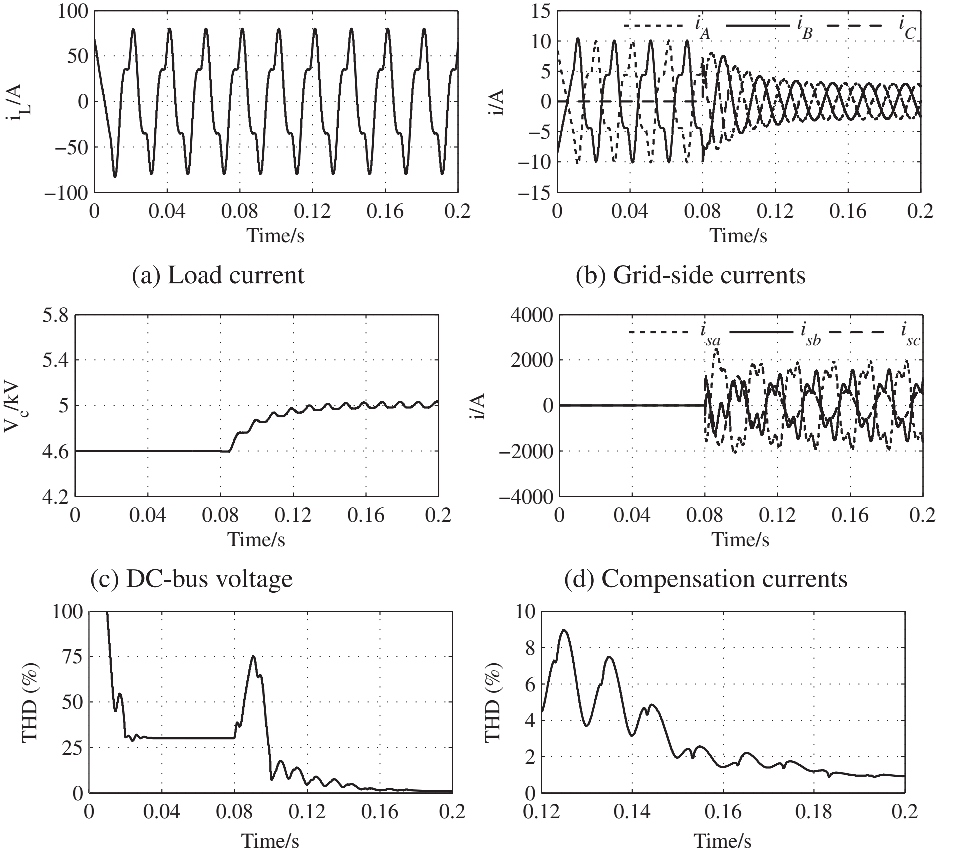


Figure 9.5 Load model of a high-speed train

Table 9.1 Parameters of the traction system

Parameters	Values
Grid-side line voltage	220 kV
K_V	220 : 27.5
K_D	27.5 : 1
L_a and L_b	1.5 mH
DC-bus capacitor	30000 μF
Initial voltage of the DC-bus capacitor	4600 V

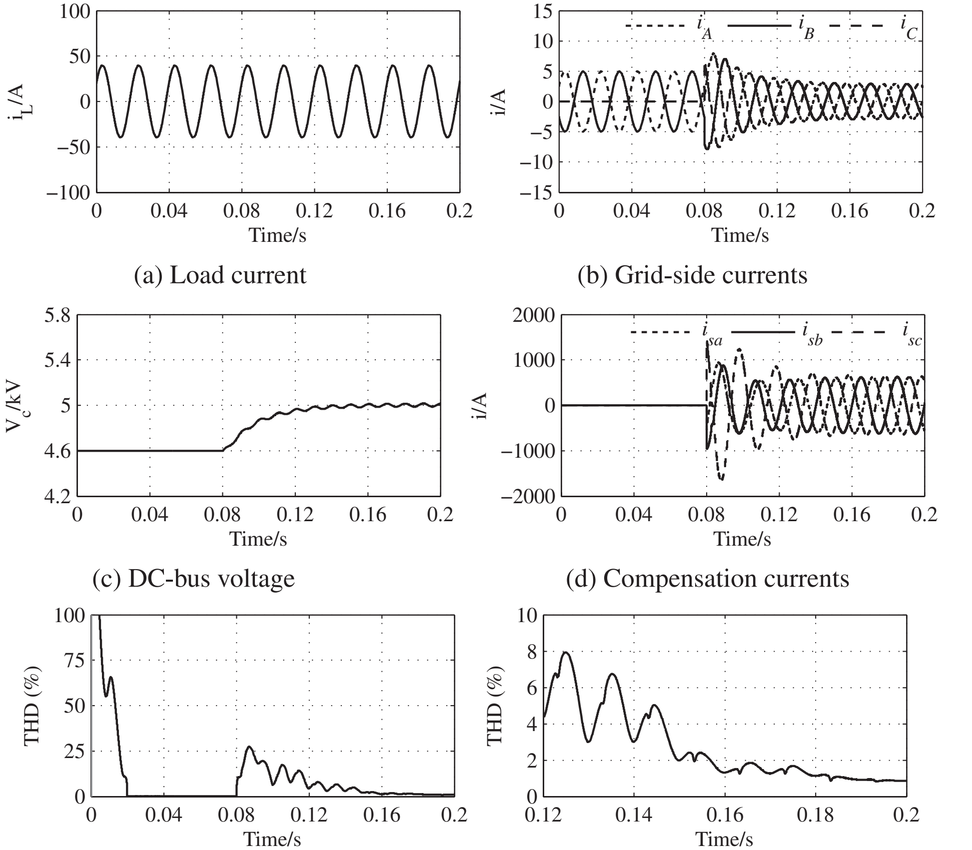


(a) Load current (b) Grid-side currents

(c) DC-bus voltage (d) Compensation currents

(e) THD of Phase-A grid-side current (f) THD of Phase-A grid-side current (0.12~0.2 s)

Figure 9.6 Effect of the compensation strategy when $\cos\theta \neq 1$



(a) Load current (b) Grid-side currents

(c) DC-bus voltage (d) Compensation currents

(e) THD of Phase-A grid-side current (f) THD of Phase-A grid-side current (0.12~0.2 s)

Figure 9.7 Effect of the compensation strategy when $\cos\theta = 1$

9.6 Summary

A topology incorporating a three-phase V/V transformer and a three-phase converter is presented for traction power systems. It provides a single feeding wire instead of two phase feeding wires. The converter is operated as a static power conditioner with a multi-functional control strategy so that it is able to balance the grid currents, to compensate for reactive power and to suppress current harmonics caused by locomotives. As a result, the power quality issues often seen in traction power systems, such as negative-sequence currents, harmonics and low power factor, are all dealt with. Compared to the traditional two-phase traction systems, this system has a simple structure and reduced neutral sections, which enhances system reliability. The strategy is validated with simulation results.