Hybrid Railway Power Conditioner with Partial Compensation for Rating Optimization

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Abstract— **The traction power supply system using single-phase traction transformer was widely used due to its low cost and simple structure. However, more heavy-loading high-speed trains are put into use. Railway power conditioner needs to be installed to increase the loading capacity of the substation and to improve the supply quality. A hybrid railway power conditioner (HRPC) is applied to the traction substation, which can reduce the reactive power, release the system unbalance and suppress the harmonics. The HRPC was originally proposed for the cophase traction power supply system with the advantage of low voltage rating, which is only 70% of the conventional railway power conditioner. Based on the system modeling, the partial compensation is introduced to further decrease the rating of the HRPC. A comprehensive design procedure is proposed for the HRPC with partial compensation for rating optimization. A reduction of more than 50% is achieved in the HRPC rating by compensating the power factor at the grid side to 0.95 instead of unity. The control block diagram is modified for the HRPC with partial compensation. The design and control of the HRPC are validated by simulation and experimental results.**

I. INTRODUCTION

The 25kV AC system has been adopted in the long-distance electrified railway in many countries. The single-phase traction transformer is widely used in traction substation due to its low cost and simple structure [1][2]. In China, the supply system of the latest high-speed railway also adopts this traction transformer, but the traction substations need to be supplied from 500kV transmission system in order to guarantee sufficient short-circuit capacity [3]. As a result, the total cost of the traction power supply system is high.

The configuration of the traction power supply system using single-phase transformer is shown in Fig.1. Electrical locomotives introduce reactive power and harmonic problems into the traction power supply systems, which make the traction transformer work in the derated mode and increase the system losses [4]-[6]. At the same time, the unbalance at the three-phase grid side remains a severe problem even the single-phase traction transformers are connected to three phases in turn [7] [8].

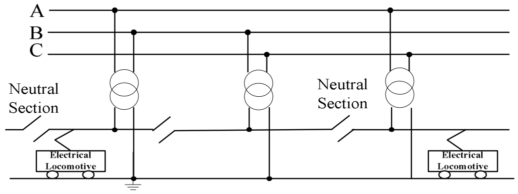

Figure 1. Traction power supply system using single-phase traction transformer

More heavy-loading high-speed trains are put into use in electrified railway system. The loading capacity of the existing traction substation needs to be increased and power quality should be controlled. Railway power conditioner (RPC) was proposed to improve the power quality in the traction power supply system [9][10]. According to the field recorded data [11], the traction loads vary from zero to around 40MW. Previous work indicates that the RPC needs to transfer half of the load active power and provide all the reactive power. To achieve this goal, the required rating of the back-to-back converter in the RPC is high.

In this paper, the hybrid railway power conditioner (HRPC) is applied to the traction substation using single-phase traction transformer [12][13]. The system configuration is shown in Fig.2. The HRPC is able to increase the loading capacity by transferring active power. At the same time, the reactive currents and harmonics of the traction loads can be compensated by the HRPC. By using the design and control method in previous work, the HRPC operation voltage is reduced to around 70% of the RPC operation voltage. However, the current rating of the two power conditioners are the same.

The partial compensation was introduced to reduce the current ratings of the RPC [14], in which the compensating currents are calculated in terms of power quality standard or user requirement. The rating of the RPC is reduced to 70% by setting power factor after compensation to 0.95 instead of 1. In order to reduce the rating of the HRPC, partial compensation is also used. However, the operation voltage of the HRPC varies and coupling impedance needs to be recalculated in order to achieve rating optimization.

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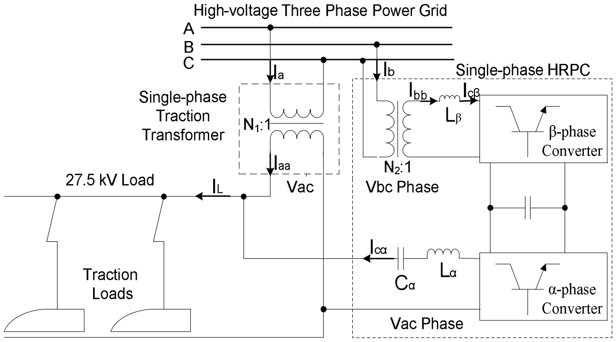


Figure 2. Traction power supply with single-phase HPRC.

In Section II, the current rating and voltage rating of the HRPC with partial compensation are first deduced. The total converter rating of the HRPC with partial compensation are evaluated in terms of the compensation target variation. In order to optimize the rating of the HRPC, a comprehensive design procedure is proposed in Section III. The control block diagram of the HRPC with partial compensation is also given in this Section. Simulation verification and experimental verification are given in Section VI and V.

II. HRPC RATING EVALUATION WITH PARTIAL COMPENSATION

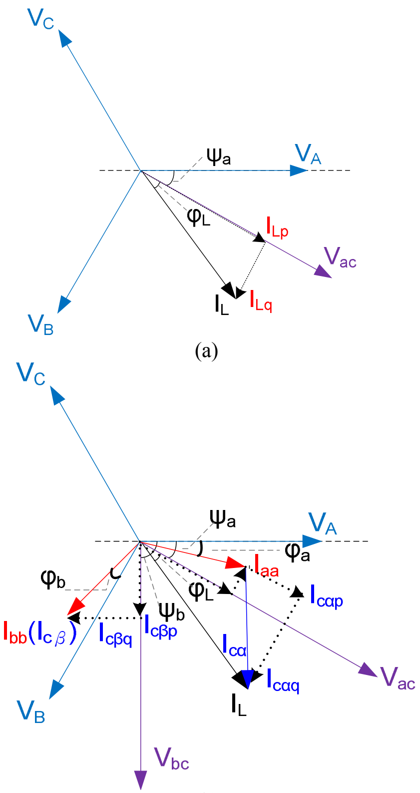
A. Current reference calculation with partial compensation

The fundamental frequency modeling of the traction power supply system without and with the HRPC is provided. When only the single-phase traction transformer operates to supply the traction loads, the phasor diagram is shown in Fig.3 (a). The voltages at the high-voltage grid side are denoted as V_A, V_B and V_C; while the secondary side voltage of the single-phase transformer is expressed as V_{ac}. The load current is I_L and its power factor is $cos\ (\varphi_L)$. The currents at the grid side are:

$$\begin{bmatrix}\dot{I}_a\\ \dot{I}_b\\ \dot{I}_c\end{bmatrix}=\frac{1}{N_1}\begin{bmatrix}I_L e^{-j(\psi_a+\varphi_L)}\\ 0\\ -I_L e^{-j(\psi_a+\varphi_L)}\end{bmatrix}, \qquad (1)$$

where N_1 is the ratio of turns of the single-phase traction transformer and $\psi_a = \pi/6$.

In Fig.2, HRPC works together with the single-phase traction transformer to supply the traction loads. The main circuit of the HRPC is a back-to-back converter, which absorbs power from the V_{bc} phase and injects to V_{ac} phase. The converter connecting to the V_{ac} phase is named the α-phase converter and the converter connecting to the V_{bc} phase is named the β-phase converter in following discussions. The output currents of these two converters are denoted as $I_{c\alpha}$ and $I_{c\beta}$. After the single-phase HRPC operates, the phasor diagram is shown in Fig. 3(b) and the currents at the grid side are given in (2), in which $\psi_b = \pi/2$.



(a)

(b)

Figure 3. Phasor diagram of traction power supply system (a) without HRPC (b) after the HRPC operates

$$\begin{bmatrix}\dot{I}_a\\ \dot{I}_b\\ \dot{I}_c\end{bmatrix}=\begin{bmatrix}\frac{1}{N_1}\dot{I}_{aa}e^{-j\psi_a}\\ \frac{1}{N_2}\dot{I}_{bb}e^{-j\psi_b}\\ -\dot{I}_a-\dot{I}_b\end{bmatrix}=\begin{bmatrix}\frac{1}{N_1}(\dot{I}_L-\dot{I}_{c\alpha})e^{-j\psi_a}\\ \frac{1}{N_2}\dot{I}_{c\beta}e^{-j\psi_b}\\ -\dot{I}_a-\dot{I}_b\end{bmatrix} \qquad (2)$$

In this paper, full compensation is defined as the case the currents at the grid side are balanced with unity power factor. The required rating of the power converters in HRPC with full compensation is used as the benchmarks to evaluate the converter ratings with partial compensation. The footnote '*f*' is used to indicate the parameters related to full compensation hereinafter. The corresponding reference currents of the HRPC are given in (3) [13] in order to achieve full compensation. The footnote '*p*' indicates current in phase with supply voltage and foot note '*q*' indicates current orthogonal to the voltage.

$$\begin{bmatrix}I_{c\alpha p\_f}\\ I_{c\alpha q\_f}\\ I_{c\beta p\_f}\\ I_{c\beta q\_f}\end{bmatrix}=\begin{bmatrix}\frac{1}{2}\cdot I_{Lp}\\ \tan(\varphi_L)I_{Lp}+\frac{\tan(\psi_a)}{2}I_{Lp}\\ \frac{N_2}{N_1}\cdot\frac{1}{2}I_{Lp}\\ \frac{N_2}{N_1}\cdot\tan(\frac{2}{3}\pi-\psi_b)\cdot\frac{1}{2}I_{Lp}\end{bmatrix} \qquad (3)$$

The current ratings of the two converters in the HRPC with full compensation are expressed as:

$$I_{c\alpha\_f} = \sqrt{(\frac{1}{2})^2 + (\tan(\varphi_L) + \frac{\tan(\psi_a)}{2})^2} I_{Lp} \tag{4}$$

$$I_{c\beta\_f} = \sqrt{(\frac{1}{2})^2 + (\frac{\tan(\frac{2}{3}\pi - \psi_b)}{2})^2} \cdot \frac{N_2}{N_1} \cdot I_{Lp} \quad . \tag{5}$$

The current references for controlling the HRPC can be adjusted to achieve partial compensation, as given in (6).

$$\begin{bmatrix} I_{c\alpha p} \\ I_{c\alpha q} \\ I_{c\beta p} \\ I_{c\beta q} \end{bmatrix} = \begin{bmatrix} k * I_{Lp} \\ \tan(\varphi_L) I_{Lp} + \tan(\psi_a - \varphi_a)(1-k) I_{Lp} \\ \frac{N_2}{N_1} * k * I_{Lp} \\ \tan(\frac{2}{3}\pi - \psi_b + \varphi_b) \frac{N_2}{N_1} * k * I_{Lp} \end{bmatrix} \tag{6}$$

The parameter '*k*' is introduced, which directly affects the percentage of the load active power supported by the HRPC. The phase angle φ_a and φ_b is set by the required power factor of the corresponding phase after HRPC operates. The parameter '*k*' also affects the reactive power injecting to the supply system since power factor reflects a ratio between the active power and reactive power. As a result, the currents at the two ports of the HRPC vary in terms of *k*, φ_a and φ_b. The current ratings of the two converters in the HRPC with partial compensation are expressed as:

$$I_{c\alpha} = \sqrt{k^2 + (\tan(\varphi_L) + \tan(\psi_a - \varphi_a)(1-k))^2} I_{Lp} \tag{7}$$

$$I_{c\beta} = \sqrt{(k)^2 + (\tan(\frac{2}{3}\pi - \psi_b + \varphi_b) \cdot k)^2} \cdot \frac{N_2}{N_1} \cdot I_{Lp} \quad . \tag{8}$$

It is assumed the load power factor is 0.85. The variation of the current ratings in terms of the power factor and *k* are shown in Fig.4. The ratings in Fig.4 are normalized by the ratings with full compensation. It can be concluded that the current ratings of the HRPC can be reduced by using partial compensation instead of full compensation.

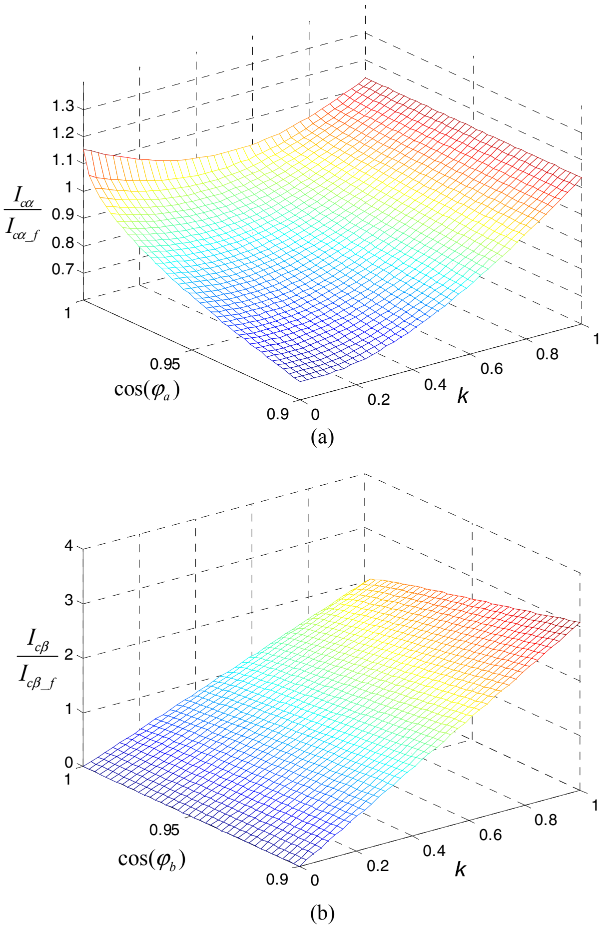
B. *Voltage ratings with partial compensation*

The voltage rating of the power converters in the HRPC also needs to be adjusted with partial compensation. The phasor diagram for α-phase converter is shown in Fig.5 and the output voltage of the α-phase converter is expressed as

$$\vec{V}_{inv\alpha} = \vec{V}_{ac} + \vec{V}_{LC} = \vec{V}_{ac} - jX_{LC} \cdot \vec{i}_{c\alpha} \quad . \tag{9}$$

The fundamental frequency impedance of the L-C branch is expressed as (10).

$$X_{LC} = \frac{1}{\omega C_\alpha} - \omega L_\alpha \cdot \tag{10}$$



(a)

(b)

Figure 4. Current ratings (a) α-phase converter (b) β-phase converter

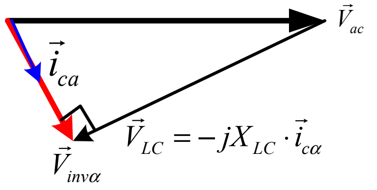


Figure 5. Phasor diagram for α-phase converter

As shown in Fig. 5, $\vec{V}_{LC}$ is $\vec{i}_{ca}$ rotating 90 degree clockwise. The output voltage varies in terms of the coupling impedance and compensating current. The voltage rating of the α-phase converter is shown in (11).

$$V_{inv\alpha} = \sqrt{(V_{ac} - I_{c\alpha q} X_{LC})^2 + (I_{c\alpha p} X_{LC})^2} \tag{11}$$

For a fixed compensating current, the optimum parameter selection of the coupling impedance X_{LC} can be determined by taking the derivative of (11) with X_{LC} and setting it as zero. The process and result are shown in (12) and (13).

$$\frac{d(V_{inv\alpha}^2)}{d(X_{LC})} = 2V_{ac} I_{c\alpha q} + 2(I_{c\alpha q}^2 + I_{c\alpha p}^2) X_{LC} = 0 \tag{12}$$

$$X_{LC} = \frac{\tan(\varphi_L) + \tan(\psi_a - \varphi_a)(1-k)}{((\tan(\varphi_L) + \tan(\psi_a - \varphi_a)(1-k))^2 + k^2} \cdot \frac{V_{ac}}{I_{Lp}} \qquad (13)$$

By substituting (6) and (13) to (11), the voltage rating of the α-phase converter is deduced as:

$$V_{inv\alpha} = \frac{k}{\sqrt{((\tan(\varphi_L) + \tan(\psi_a - \varphi_a)(1-k))^2 + k^2}} \cdot V_{ac} \qquad (14)$$

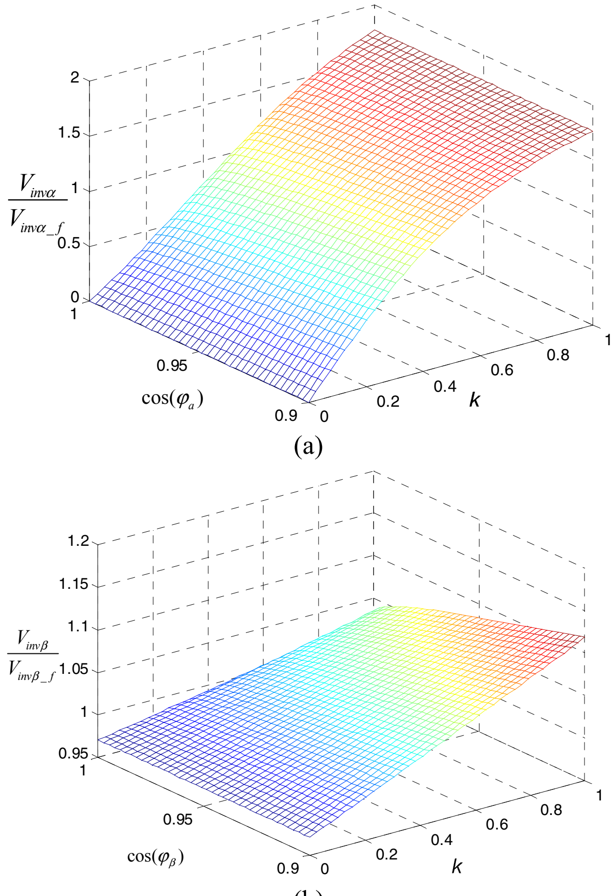
The voltage rating with full compensation is:

$$V_{inv\alpha\_f} = \frac{1/2}{\sqrt{((\tan(\varphi_L) + \tan(\psi_a)(1/2))^2 + (1/2)^2}} \cdot V_{ac}$$

Similar to the current rating, the voltage rating also varies in terms of the power factor and *k*, as illustrated in Fig. 6 (a). The voltage rating of the α-phase converter can be greatly reduced if partial compensation is adopted.

The phasor diagram for the β-phase converter is shown in Fig.7 and the output voltage of the β-phase converter is expressed as

$$\vec{V}_{inv\beta} = \vec{V}_{bc} - \vec{V}_L = \vec{V}_{bc} - jX_L \cdot \vec{i}_{c\beta} \quad . \qquad (15)$$



(a)

(b)

Figure 6. Voltage ratings (a) α-phase converter (b) β-phase converter

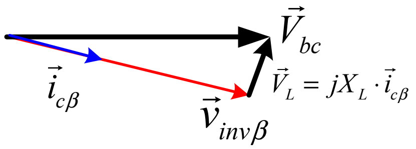


Figure 7. Phasor diagram for β-phase converter

The fundamental frequency impedance of the coupling inductor is expressed as (16).

$$X_L = \omega L_\beta \cdot \qquad (16)$$

As shown in Fig. 7, $\vec{V}_L$ is $\vec{i}_{c\beta}$ rotating 90 degree counterclockwise. The output voltage varies in terms of the coupling impedance and compensating current. The voltage rating of the β-phase converter is shown in (17).

$$V_{inv\beta} = \sqrt{(V_{bc} - I_{c\beta q} X_L)^2 + (I_{c\beta p} X_L)^2} \qquad (17)$$

The β-phase converter is coupled to the V_{bc} phase via an inductor, which is usually selected to suppress the output current ripple and is kept as small as possible. It is assumed the impedance of the coupling inductor is:

$$X_L = m \cdot \frac{V_{bc}}{(N_2/N_1) I_{Lp}} \qquad (18)$$

By substituting (6) and (18) to (17), the voltage rating of the β-phase converter is deduced as:

$$V_{inv\beta} = \sqrt{(1 - \tan(\frac{2}{3}\pi - \psi_b + \varphi_b) \cdot m \cdot k)^2 + k^2 \cdot m^2} \cdot V_{bc} \qquad (19)$$

The voltage rating with full compensation is:

$$V_{inv\beta\_f} = \sqrt{(1 - \frac{1}{2}\tan(\frac{2}{3}\pi - \psi_b) \cdot m)^2 + \frac{1}{4} \cdot m^2} \cdot V_{bc} \quad . \qquad (20)$$

The variations of the β-phase converter voltage rating in terms of the power factor and k are shown in Fig. 6 (b). *m* is set to 10% when Fig.6(b) is drawn. It can be concluded from Fig. 6(b) that the voltage rating of the β-phase converter varies in a small range when power factor and *k* varies.

C. Rating of the HRPC under partial compenation

The rating of the power converters in the HRPC is evaluated in this section. The rating of the HRPC is calculated by:

$$S_{HRPC} = S_\alpha + S_\beta = V_{inv\alpha} \cdot I_{c\alpha} + V_{inv\beta} \cdot I_{c\beta} \quad . \qquad (21)$$

It is assumed $\cos(\varphi_a) = \cos(\varphi_b)$, the variation of the ratings of the HRPC in terms of the power factor and *k* is shown in Fig.8. By adopting partial compensation, the total power converter ratings in the HRPC can be reduced to less than 50% of that required by full compensation.

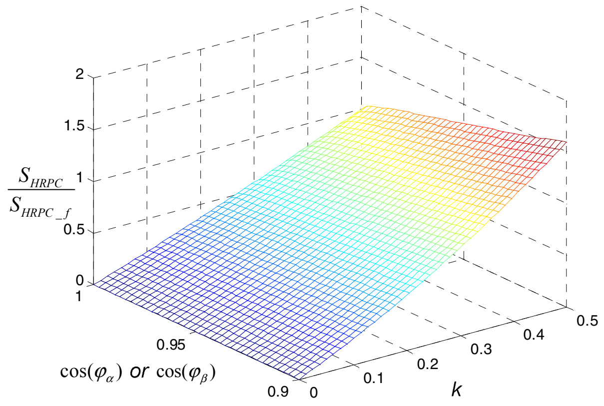


Figure 8. Rating of the HRPC varies in terms of power factor and *k*

III. SYSTEM DESIGN AND IMPLEMENTATION

Based on previous analyses, design the HRPC with partial compensation can reduce the rating of the power converters. One method to select the power factor and to calculate the parameter *k* was proposed for RPC in cophase traction power supply system [14]. The grid side power factor is first set according to the power quality tariff plan in China, in which the penalty for reactive power can be avoided if the power factor is higher than 0.9. To achieve the same grid side power factor, *k* value may vary in terms of different power factor settings for each phase. The minimum current rating is obtained by setting the power angle of phases A and B lagging and the power angle of phase C leading under partial compensation. This scheme is also used in this paper to design the HRPC under partial compensation. With the selected power factor and *k*, the coupling impedance and dc-link voltage of the HRPC are designed accordingly. The comprehensive design procedure of the HRPC is presented as follows.

1. Set the power factor to be achieved after HRPC operates.

$$PF_{grid} = (P_A + P_B + P_C)/(S_A + S_B + S_C) \tag{22}$$

2. Calculate the k according to (23), in which phase angles are calculated by (24).

$$k = \frac{\cos(\psi_b - \varphi_b - \frac{2}{3}\pi)\sin(\varphi_a - \varphi_c + \frac{2}{3}\pi)}{\cos(\psi_b - \varphi_b - \frac{2}{3}\pi)\sin(\varphi_a - \varphi_c + \frac{2}{3}\pi) + \cos(\psi_a - \varphi_a)\sin(\varphi_c - \varphi_b + \frac{2}{3}\pi)} \tag{23}$$

$$\varphi_a = \varphi_b = -\varphi_c = a\cos(PF_{grid}) \tag{24}$$

3. The reference currents for controlling the HRPC is calculated by (25).

$$\begin{bmatrix} I_{c\alpha p} \\ I_{c\alpha q} \\ I_{c\beta p} \\ I_{c\beta q} \end{bmatrix} = \begin{bmatrix} k * I_{Lp} \\ \tan(\varphi_L) I_{Lp} + \tan(\psi_a - \varphi_a)(1-k) I_{Lp} \\ \frac{N_2}{N_1} \cdot k \cdot I_{Lp} \\ \tan(\frac{2}{3}\pi - \psi_b + \varphi_b) \frac{N_2}{N_1} \cdot k \cdot I_{Lp} \end{bmatrix} = \begin{bmatrix} k * I_{Lp} \\ \tan(\varphi_L) I_{Lp} + k_\alpha I_{Lp} \\ \frac{N_2}{N_1} \cdot k \cdot I_{Lp} \\ \frac{N_2}{N_1} \cdot k_\beta \cdot k \cdot I_{Lp} \end{bmatrix} \tag{25}$$

4. Calculate the fundamental frequency coupling impedance of the α-phase converter.

$$X_{LC} = \frac{\tan(\varphi_L) + \tan(\psi_a - \varphi_a)(1-k)}{((\tan(\varphi_L) + \tan(\psi_a - \varphi_a)(1-k))^2 + k^2} \cdot \frac{V_{ac}}{I_{Lp}} \tag{26}$$

5. Calculate the α-phase coupling inductor and capacitor. The harmonic compensation is taken into consideration. The load harmonic current at hth harmonic is assumed to be r_h times of fundamental, as given in (27). The coupling impedance is chosen to minimize the harmonic operation voltage [15], as given in (28) and (29).

$$I_{Lh} = r_h \cdot I_{L1} = r_h \cdot I_{L1p} / \cos(\varphi_L) \tag{27}$$

$$L_a = \frac{\dfrac{\sum_{h=2}^{\infty} (r_h)^2 \cdot \dfrac{2(h^2-1)}{h^2}}{\sum_{h=2}^{\infty} (r_h)^2 \cdot \dfrac{2(h^2-1)^2}{h^2}}}{\omega_1} X_{LC} = \frac{k_L}{\omega_1} X_{LC} \tag{28}$$

$$C_a = \frac{1}{\omega_1 \left(1 + \dfrac{\sum_{h=2}^{\infty} (r_h)^2 \cdot \dfrac{2(h^2-1)}{h^2}}{\sum_{h=2}^{\infty} (r_h)^2 \cdot \dfrac{2(h^2-1)^2}{h^2}} \right) \cdot X_{LCa}} = \frac{1}{\omega_1 k_c \cdot X_{LC}} \tag{29}$$

6. Calculate the β-phase coupling inductor according to (18) and (30).

$$L_\beta = \frac{X_L}{\omega_1} \tag{30}$$

7. Determine the DC link operation voltage in HRPC according to (31).

$$V_{dc} = \sqrt{2} \sqrt{V_{inv\alpha}^2 + \sum_{h=2}^{\infty} (X_{LCh} \cdot I_{Lh})^2} \tag{31}$$

where $X_{LCh} = -\frac{1}{h}\left[\left(h^2 - 1\right) k_L - 1 \right] X_{LC}$.

Fig. 9 illustrates the control diagram of the proposed HRPC. The partial compensation is achieved by multiplying the corresponding coefficient to power reference of each phase. The coefficients are defined in (25). By varying these coefficients, the HRPC is controlled to achieve the designed compensation target. .

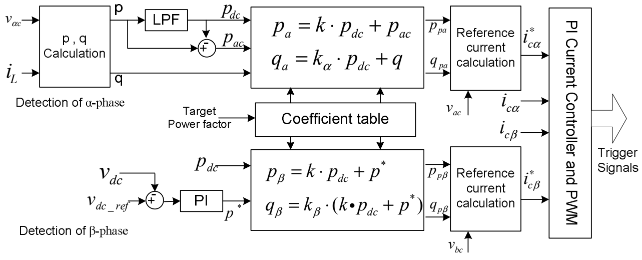


Figure 9. Control system of the hybrid railway power conditioner

IV. CASE STUDY AND SIMULATION

A case study is presented in this Section in order to verify the analysis and the comprehensive design procedure developed in previous parts. The traction substation uses one single-phase traction transformer. The primary side of the traction transformer is connected to 110kV power grid and its secondary side provides 27.5kV supply to the traction loads. The traction load is of 15 MVA, and load power factor of 0.85. The system source impedance is calculated as 2 mH according to the short circuit capacity of common traction power supply 750 MVA. Shown in Table I is the practical on-site data of the harmonic distribution in traction load of WuQing substation in China [16]. A HRPC is installed to improve the power quality. The parameters designed for HRPC with full compensation are listed in Table II .

The target of the partial compensation is set according to the utility tariff plan for the reactive power. For example, PF is at least 0.9 in order to avoid penalty. For the traction motor, more reactive power is consumed during the motor starting. To cope with this particular case, it is better to overdesign the reactive power compensation capability. A safety margin is required considering possible over-loading, 0.95 is used as the power factor to design the HRPC in this paper. The obtained system parameters are listed in Table II.

Simulation models are built by using PSCAD. The circuit schematics can be found in Fig. 2. The load harmonics are designed according to the data in Table I. The grid side voltages and currents without HRPC are shown in Fig. 10. It can be concluded the traction load currents are severely unbalanced with low power factor and high harmonics.

TABLE I. ON-SITE STATISTICS OF HARMONIC CURRENT CONTENTS IN WUQING SUBSTATION TRACTION LOAD.

	3rd	**5th**	**7th**	**9th**	**11th**
Harmonic contents (% of fundamental)	10.81	7.96	4.51	3.04	2.68

TABLE II. PARAMETER DESIGNED FOR HRPC

No.	**Items**	**Full**	**Partial**
1	Tractioin transformer	110kV/27.5kV	
2	β-phase Coupling Transformer	190kV/9.167kV	
3	k k_α k_β	0.5, 0.2887, 0.5774	0.2154, 0.1640, 1.1182
4	α-phase Coupling Inductor L_α	6.6 mH	9.3 mH
5	α-phase Coupling Capacitor C_α	61.01 uF	43.45 uF
6	β-phase Coupling Inductor L_β	8 mH	10 mH
7	V_{dc}	18.7 kV	11kV

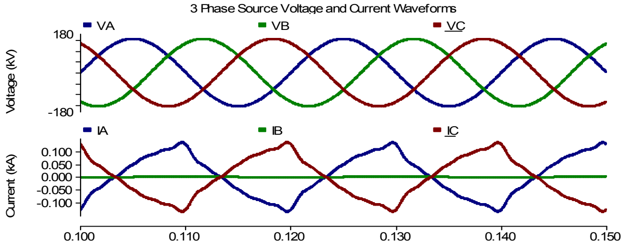


Figure 10. Grid side voltage and current waveforms without HRPC

The full compensation is first achieved by the HRPC using a dc voltage of 18.7kV. The grid side voltages and currents after compensation are shown in Fig.11. The three-phase currents are balanced with unity power factor. The harmonics are also eliminated. The system performance is summarized in Table III, in which the HRPC rating is calculated by:

$$S_{HRPC} = S_\alpha + S_\beta = \frac{V_{dc}}{\sqrt{2}}(I_{c\alpha} + I_{c\beta}) \tag{32}$$

By designing the HRPC with partial compensation, the dc voltage is reduced to 11kV. The simulation results of the grid side currents are shown in Fig.12 when the HRPC is controlled to achieve full compensation with 11kV dc voltage. It is obvious the HRPC fails to improve the power quality of the traction power supply system. The control block diagram in Fig.9 is adopted to modify the reference of the HRPC. The corresponding simulation results are illustrated in Fig.13 and Table III. The power factor is improved to around 0.95. The harmonics are suppressed and the current unbalance is improved.

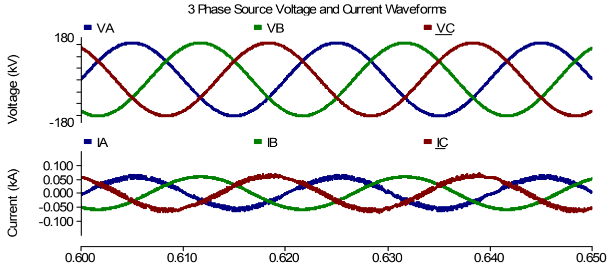


Figure 11. Grid side voltage and current waveforms with HRPC setting to achieve full compensation (Vdc = 18.7kV)

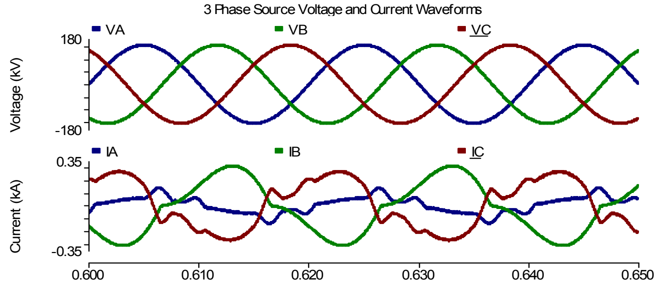


Figure 12. Grid side voltage and current waveforms with HRPC setting to achieve full compensation (Vdc = 11 kV)

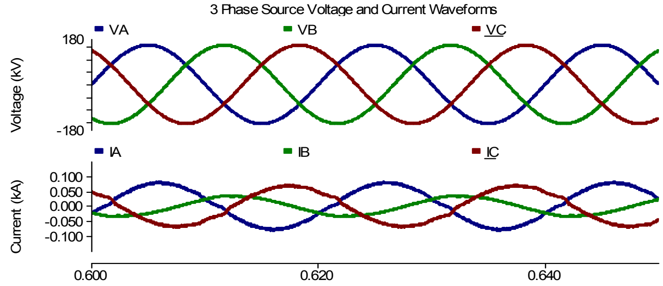


Figure 13. Grid side voltage and current waveforms with HRPC setting to achieve partial compensation (power factor = 0.95, Vdc = 11 kV)

TABLE III. SYSTEM PERFORMANCE IN SIMULATION

Condition	Power Factor	Source Current THD (phase A)	Current Unbalance	HRPC Rating (MVA)
Before Compensation	0.60	14.7%	100%	---
HRPC with full compensation(V_{dc}=18.7kV)	0.997	2.34%	4.75%	15.13
HRPC with full compensation(V_{dc}=11kV)	0.985	37.9%	22.63%	10.5
HRPC with partial compensation(V_{dc}=11kV)	0.954	3.27%	44%	6.97

V. EXPERIMENTAL RESULTS

A small capacity prototype was built and the system configuration is the same as Fig.2. The peak value of the sinusoidal three-phase supply voltage is 70.7V. The load is constructed by a single-phase rectifier and its harmonic distribution is given in Table IV. The corresponding parameters designed for the experiment are listed in Table V. The system waveforms are captured using Yokogawa DL750 16 channel ScopeCorder Oscilloscope and Fluke three-phase Power Quality Analyzer. The results are given in Fig. 14 and Table IV.

The grid side voltages and currents are shown in Fig.14(a) without the HRPC operating. The system waveforms obtained with HRPC under full compensation are presented in Fig.14 (b). It can be observed that compared to Fig. 14(a), unbalance current, reactive current and harmonics are compared simultaneously. The dc link voltage under this case is 41V, which is lower than the grid-side voltage.

Next, experimental results are done by adjusting the compensation target. The power factor is set to 0.95 and the parameters in control blocks are modified accordingly. The waveforms obtained with HRPC under partial compensation are presented in Fig. 14(c). The dc link voltage is reduced to 24V. The reactive current and unbalance are partially compensated. The harmonics are eliminated as illustrated in Fig.14 and Table VI. With enough short-circuit capacity, the power quality standard is satisfied but the converter rating is reduced to 43% of that required by full compensation. Not only the system initial cost is reduced, the operation losses are also reduced as the dc voltage is lower.

TABLE IV. HARMONIC CURRENT CONTENTS IN TESTING LOAD.

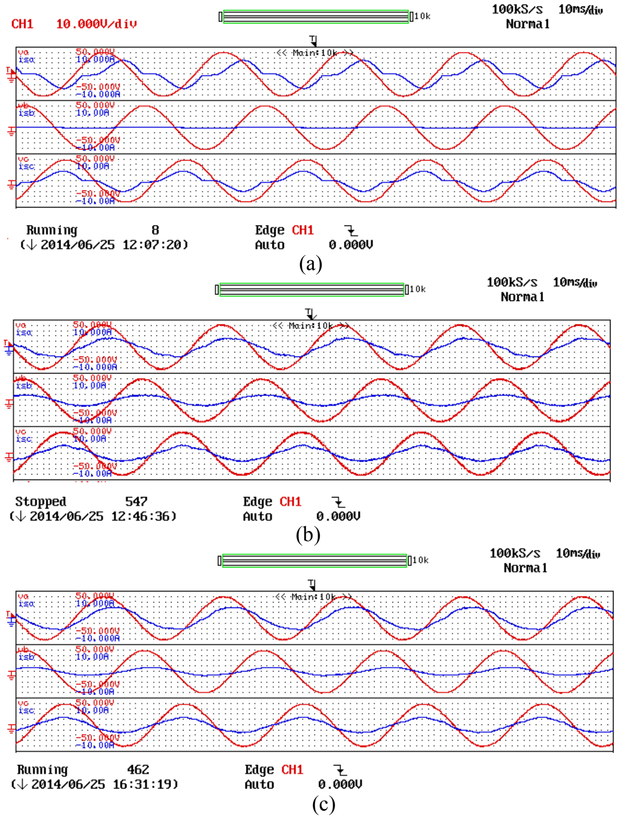
	3rd	5th	7th	9th	11th
Harmonic contents (% of fundamental)	27.9%	5.7%	2.0%	1.5%	1.2%

TABLE V. PARAMETER DESIGNED FOR HRPC IN EXPERIMENT

No.	Items	Full	Partial
1	Tractioin transformer	220V/50V	
2	β-phase Coupling Transformer	220V/25V	
3	α-phase Coupling Inductor L_α	6.7 mH	6.7 mH
4	α-phase Coupling Capacitor C_α	190 uF	120 uF
5	β-phase Coupling Inductor L_β	10 mH	10 mH
6	V_{dc}	41V	24V

TABLE VI. SYSTEM PERFORMANCE IN EXPERIMENT

Condition	Power Factor	Source Current THD(phase A)	Current Unbalance	HRPC Rating
Before Compensation	0.76	28.6%	92.2%	---
HRPC with full compensation	0.95	9.1%	26%	142.3VA
HRPC with partial compensation	0.94	6.9%	43.3%	62.97VA



(a)

(b)

(c)

Figure 14. Experimental Results: three-phase voltages and currents at the grid side (a) Without HRPC (b) HRPC with full compensation (c) HRPC with partial compensation

VI. CONCLUSIONS

In this paper, a HRPC is applied to the traction power supply system using single-phase traction transformer. The partial compensation is introduced to reduce the required rating of the back-to-back converter in HRPC. A comprehensive design method is proposed for the HRPC with partial compensation to achieve rating optimization. The control block diagram is also modified in terms of the set grid side power factor after HRPC operates. The rating of the HRPC is reduced by more than 50% if the grid side power factor is set to 0.95 instead of one. The initial cost and size of the system is greatly reduced. The design and control of the HRPC with partial compensation is verified by simulation. A small-capacity experimental prototype is built in the laboratory and testing results are also provided.

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