A Systematic Approach to Hybrid Railway Power Conditioner Design With Harmonic Compensation for High-Speed Railway

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***Abstract*—Cophase traction power system has high potential to be power supply for high-speed railway. However, the dc operation voltage of conventional power quality compensation device within, such as railway power quality conditioner, is high and may limit its application and development. The hybrid power quality conditioner (HPQC), in which a capacitive coupled LC structure is added, is thus proposed for lower operation voltage. However, there is less investigation and study on the HPQC parameter design for minimum operation voltage when harmonic compensation is concerned. In this paper, the HPQC design for minimum dc operation voltage under comprehensive fundamental and harmonic compensation is being proposed and introduced. Analysis and case study are also performed to show the advantage of the proposed HPQC design. Simulation and laboratory-scaled experimental results are presented to show effective reduction in dc operation voltage using the proposed HPQC design. Through the simulation and experimental case study and verification, there is a reduction of 15% in operation voltage using the proposed hybrid LC structure design compared with the conventional design. The proposed design does not add much additional cost and can also reduce the coupling inductance value. Similar analysis procedure may be also applied to other LC hybrid-structured active power compensators.**

***Index Terms*—Cophase traction, high-speed locomotive, hybrid filter, power quality compensation.**

I. Introduction

SINGLE-PHASE ac power supply has been widely adopted in long-distance electrified railway in many countries. Electrical locomotives introduce reactive power and harmonic problems into the traction power supply systems. As the amount of rail traffic increases, the issue of power quality distortion is becoming more critical [1]–[5]. Moreover, electrical isolations such as neutral sections between power regions are required, which causes reduction in locomotive speed [6], [7]. As a result, a traction power supply suitable for high-speed railway is required to overcome the aforementioned issues.

There are various techniques to relieve the unbalance problem, such as usage of Scott, YNvd, V/V, and impedance-matching transformers. However, due to traction load variations, these solutions cannot completely compensate the unbalance problem. The reactive power and harmonic portions can be compensated by passive compensators such as capacitor banks and filters. Compared with passive compensators, active compensators can provide better dynamic and comprehensive compensation. The most commonly used compensators in traction power supply are static VAR compensator (SVC) and static synchronous compensator (STATCOM). In [8], the compensation performance using SVC for voltage regulation of a 25-kV traction is explored. However, its dynamic response is poor, and compensation results are not satisfactory when the load is varying. Furthermore, the high-power SVC occupies a large area. Hereafter, active power filter (APF) is proposed to provide fast and dynamic response. Unfortunately, the device rating of APF is still too high. In [9], compensation device based on hybrid structure is therefore proposed for lower device rating.

At around 2004, field-tested results of a railway static power conditioner (RSPC) in Shinkansen, Japan, were reported [10], in which RSPC studies about using active power conditioners operating together with the balance transformer could be found in [11]–[14]. A simplified multilevel railway power conditioner (RPC) based on half-bridge converter has been also proposed [15]. Furthermore, in 2009, cophase traction power supply system is being introduced as one of the newly proposed traction power systems, which can solve the problem of excessive neutral sections installation in traction power supplies [6], [16]–[18]. Elimination of neutral sections may reduce the velocity loss in locomotives, and thus, cophase traction power has high potential as a high-speed traction power supply system. Therefore, usage of cophase traction power supply has been investigated as a system that can overcome the aforementioned issues and has been mostly suggested in recent studies.

At around 2012, in [4], a hybrid device combining active and passive compensators, which is named as the hybrid power

Manuscript received July 9, 2013; revised October 19, 2013, January 13, 2014, and April 15, 2014; accepted May 20, 2014. Date of publication July 22, 2014; date of current version January 7, 2015. This work was supported in part by the Science and Technology Development Fund under Project 015/2008/A1, in part by the Macao SAR Government, and in part by the University of Macau Research Committee under Project UL015/08-Y2/EEE/WMC01/FST and MYRG2014-00024-FST.

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Digital Object Identifier 10.1109/TIE.2014.2341577

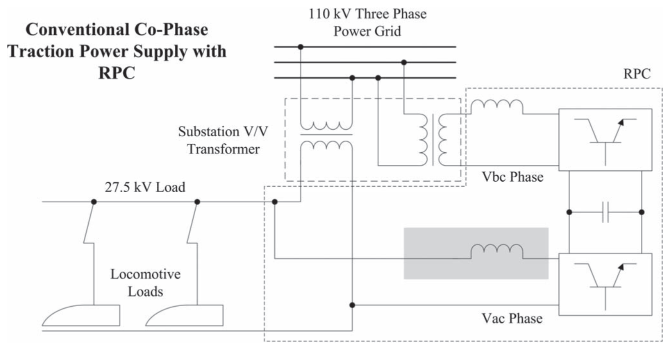

Fig. 1. Cophase traction power supply with the conventional RPC.

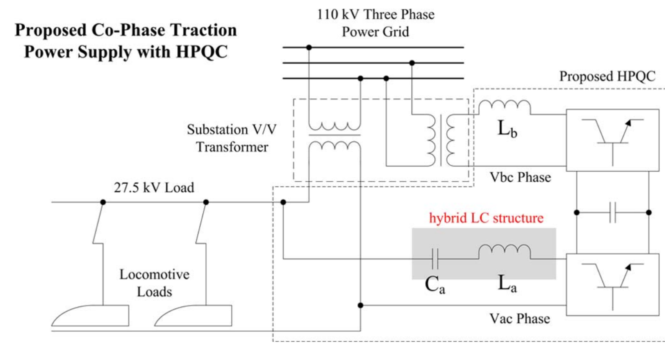

Fig. 2. Cophase traction power supply with the proposed HPQC.

quality compensator (HPQC), was proposed for compensation in cophase traction power supply. This approach is advantageous not only for reduction in system capacity and initial cost but also the reduction of converter switching operation loss compared with conventional cophase traction power supply system. Hereafter, minimum dc operation voltage design of this HPQC under fundamental compensation of system unbalance and reactive power was discussed in [19]. However, in [19], there is no detailed description of HPQC design under comprehensive compensation, including considerations of both fundamental and harmonic compensation. Moreover, it has been mostly suggested that the resonant frequency of the passive LC branch of a hybrid-structured compensator can be tuned to the frequency where system harmonics are mostly concentrated at to minimize the dc operation voltage of the compensator. [20]–[22]. However, the idea still lacks theoretical support or mathematical derivation.

In this paper, the comprehensive HPQC design for minimum operation voltage under both fundamental and harmonic compensation is discussed. In Section I, the control principle of comprehensive power quality compensation of system unbalance, reactive power, and harmonics in cophase traction power supply is introduced. In order to show the advantages of HPQC over RPC, the motivation and differences of the proposed HPQC structure from the conventional RPC one is reviewed in Section II. Afterward, in Section III, the proposed HPQC design for minimum operation voltage is mathematically derived for fundamental and harmonic compensation, respectively, to provide the comprehensive design procedure. A case study is also performed based on the on-site data obtained from the WuQing traction substation in China for verification. The simulated results are presented in Section IV, whereas experimental verifications are given in Section V to show the advantages of the proposed HPQC design. Finally, conclusion is provided in Section VI, which summarizes the proposed idea and verification results.

II. Comparisons Between Cophase Traction With Conventional RPC and Proposed HPQC

First of all, the compensation theory is briefly introduced. The system configurations of a typical cophase traction power with the conventional RPC and the proposed HPQC are shown in Figs. 1 and 2, respectively. The power quality compensator is connected across the transformer.

The required output compensation power from a cophase traction power quality compensator is shown in the following:

$$\begin{bmatrix} p_{ca} \\ q_{ca} \\ p_{cb} \\ q_{cb} \end{bmatrix} = \begin{bmatrix} K_1 p_{dc} + p_{ac} \\ K_2 p_{dc} + q \\ -K_1 p_{dc} \\ -K_2 p_{dc} \end{bmatrix}. \tag{1}$$

The three-phase power quality in cophase traction power supply is first modeled, as shown in (2). Different parameters within can be determined by the power quality requirement. Furthermore, during compensation, no active power is stored by the compensator, whose mathematical relationship is shown in (3). Thus,

$$\begin{cases} PFA = \cos(30^\circ + \varphi_a) \\ PFB = \cos(-30^\circ + \varphi_b) \\ PFC = \cos\left(-240^\circ + \tan^{-1}\left(\frac{I_a \sin\phi_a + I_b \sin\phi_b}{-I_a\cos\phi_a - I_b\cos\phi_b}\right)\right) \\ \text{Unbalance}: \\ \quad |\dot{I}^-| = \frac{1}{\sqrt{3}K}\sqrt{I_a^2 + I_b^2 + 2I_aI_b\cos(-120^\circ + \varphi_a - \varphi_b)} \\ I_h = \sqrt{\sum_{n=2}^{\infty} I_n^2} \end{cases} \tag{2}$$

where $\phi_a = \psi_a + \varphi_a$ and $\phi_b = \psi_b + \varphi_b$

$$I_a \cos\varphi_a + I_b \cos\varphi_b = I_L \cos\varphi_L = I_{Lp}. \tag{3}$$

By solving the equations in (2) and (3), the required primary source current I_a, I_b, and I_c, as well as the power angles, can be calculated. This can be then transformed into secondary side current, which can be used to deduce the compensating current by simple circuit analysis. The parameters K_1 and K_2 in (1) can be thus determined. Detailed derivations of constants $K_1 = 0.5$ and $K_2 = 0.2887$ were explained in [4] and [25] for full compensation.

It is worth noticing that the negative sign in (1) refers to power absorption and the two converters in cophase power compensator. During compensation, active and reactive power is absorbed from one phase and transferred to another phase. The two converters in HPQC thus have different power transfer functions.

Based on the instantaneous pq theory [23], [24] and (1), the compensator control system block diagram is presented in Fig. 3. The instantaneous load active and reactive power is first computed and is used to determine the required compensation power p_{ca}, q_{ca}, p_{cb}, and q_{cb} and, thus, the required

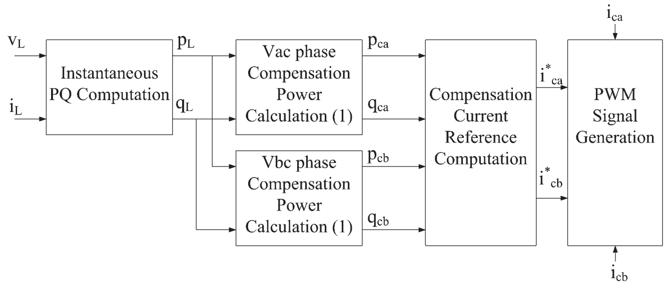

Fig. 3. Control block diagram of compensation in cophase traction power supply.

compensation current. They are used to generate pulsewidth modulation (PWM) signals, which are used to control the electronic switches insulated-gate bipolar transistors within the compensator to output the required compensation current.

The discussions that follow are developed based on the theory above. Differences of configuration and operation of the conventional RPC and the proposed HPQC are discussed.

A. Converter Topology

With reference to Figs. 1 and 2, it can be observed that both the conventional RPC and the proposed HPQC are a back-to-back converter with a common dc link. The major difference between them is the Vac phase coupled structure. In the conventional RPC, it is an inductive coupled structure, and in the proposed HPQC, it is a hybrid inductor–capacitor (LC) capacitive coupled structure. The passive structure in HPQC can help to reduce the operation voltage during compensation. This will be covered in the next subsection.

B. Operation Voltage

In addition to converter topology, another difference is that the operation voltage of the proposed HPQC is lower than that of the conventional RPC. The vector diagram showing their operation voltage is presented in Fig. 4. The mathematical relationship is shown in the following:

$$|V_{\text{invaL}}| = \sqrt{V_{\text{invaLp}}^2 + V_{\text{invaLq}}^2} = \sqrt{(V_{ac} + |I_{caq}|X_{La})^2 + (|I_{cap}|X_{La})^2} \quad (4)$$

$$|V_{\text{invaLC}}| = \sqrt{V_{\text{invaLCp}}^2 + V_{\text{invaLCq}}^2} = \sqrt{(V_{ac} - |I_{caq}|X_{\text{LCa}})^2 + (|I_{cap}|X_{\text{LCa}})^2}. \quad (5)$$

It can be observed that, in contrast to the conventional RPC, when reactive current passes through the hybrid LC capacitive coupled structure in the proposed HPQC, there is a positive active power drop across the source and the converter side. The operation voltage of the proposed HPQC can be thus lower than Vac point-of-common-coupling (PCC) voltage while providing similar compensation performance like the conventional RPC.

The HPQC operation voltage can be minimized when an appropriate coupled impedance value is being selected. By taking the first derivative of (4) with respect to X_{LCa} and setting the result to zero, the value of X_{LC} where V_{invaLC} is at extreme point can be then obtained, as given in (6), where θ_{ca} refers to the power angle of the Vac compensation current I_{ca}. Fig. 5 explained this minimum operation voltage using a vector diagram, in which $V_{\text{invLC\_min}} = V_{\text{invaLC\_min}}$, which is consistent with the mathematical analysis. Thus,

$$V_{\text{LCa}}[V_{\text{invaLC\_min}}] = -I_{ca}X_{\text{LCa}} = V_{ac}(\sin\theta_{ca}). \quad (6)$$

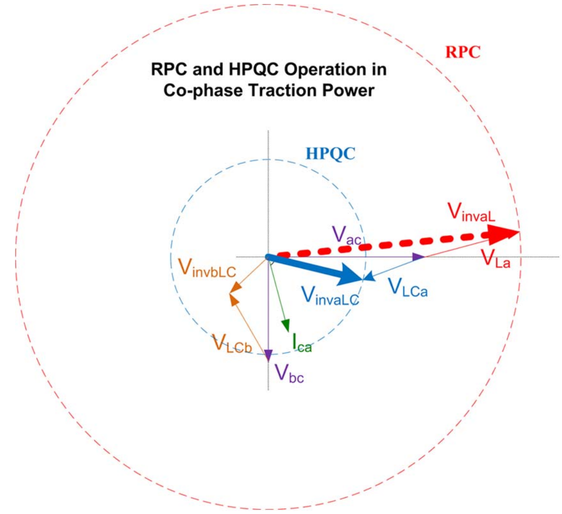

Fig. 4. Cophase traction power supply with the conventional RPC.

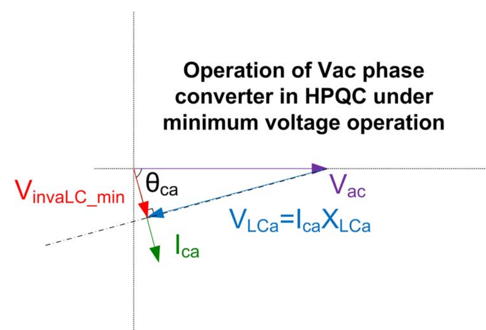

Fig. 5. Vector diagram showing the minimum operation dc voltage of HPQC.

In short, the HPQC operation voltage is reduced via coupling impedance design. Since locomotives are mostly composed of motors and are inductive, a capacitive coupled structure can help to eliminate the inductive reactive power and thus reduce the compensation requirement and operation voltage of the compensator [4], [19].

Based on the discussions above, it can be seen that the addition of coupling capacitor in HPQC is advantageous for reduced operation voltage compared with RPC while providing similar performance. Reduction in operation voltage can help to reduce the cost and switching power loss.

III. Comprehensive HPQC Compensator Parameter Design Based on Minimum Operation Voltage

The usage of HPQC operation voltage may be divided according to two purposes: fundamental (V_{invaLC1}) and harmonic

(V_{invaLCh}) compensation. This idea may be mathematically represented, as shown in (7), and the parameters are defined in (8) and (9). In traction load, fundamental compensation occupies most of the compensation capacity. Here, the comprehensive HPQC design will be presented based on the criteria of minimizing the operation voltage for providing these two compensation modes. Thus,

$$V_{\text{invaLC}} = \sqrt{V_{\text{invaLC1}}^2 + V_{\text{invalCh}}^2} \tag{7}$$

$$V_{\text{invaLC1}}^2 = (V_{ac} + |I_{caq1}|X_{\text{LCa}})^2 + (|I_{cap1}|X_{\text{LCa}})^2 \tag{8}$$

$$V_{\text{invaLCh}}^2 = \sum_{h=2}^{\infty} I_{\text{Lh}}^2 X_{\text{LCah}}^2. \tag{9}$$

A. HPQC Design of Minimum Operation Voltage for Fundamental Compensation

Fundamental compensation in cophase traction power supply includes basic compensation for system unbalance and reactive power. In short, the operation voltage for fundamental compensation is the required operation voltage to provide power quality compensation (of system unbalance and reactive power) without harmonic compensation. It dominates the major portion of power quality compensation, as harmonics are usually less significant compared with reactive power and system unbalance in a power system.

The design of HPQC Vac coupled impedance has been discussed in the previous section. The optimum parameter selection of Vac phase coupled impedance X_{LCa} may be also determined by taking the derivative of (8) with X_{LCa} and setting it as zero. The process and result are shown in (10) and (11). It is consistent with the expression in (6). Notice that the negative sign in the expression refer to a capacitive coupled impedance. Thus,

$$\frac{d\left(V_{\text{invaLC1}}^2\right)}{d(X_{\text{LCa}})} = V_{ac}|I_{caq1}| + X_{\text{LCa}}\left(|I_{caq1}|^2 + |I_{caq1}|^2\right)$$
$$= 0 \tag{10}$$

$$X_{\text{LCa}} = -\frac{V_{ac}\sin\theta_{ca}}{I_{ca}}. \tag{11}$$

B. HPQC Design of Minimum Operation Voltage for Harmonic Compensation

Although fundamental system unbalance and reactive power compensation occupy the major portion of power quality compensation capacity, harmonic compensation cannot be neglected as it will also add to the overall compensator operation voltage requirement. With reference to (9), it can be observed that the discussion relates also to the harmonic impedance that an optimum selection of coupled inductance L_a and C_a must be chosen to minimize the harmonic operation voltage V_{invaLCh}. Here, the discussion of the HPQC design is presented based on the criteria of minimum fundamental operation voltage V_{invaLC1} in (11). In other words, the parameter design for minimum operation voltage during harmonic compensation developed here does not alter the fundamental coupled impedance X_{LCa}.

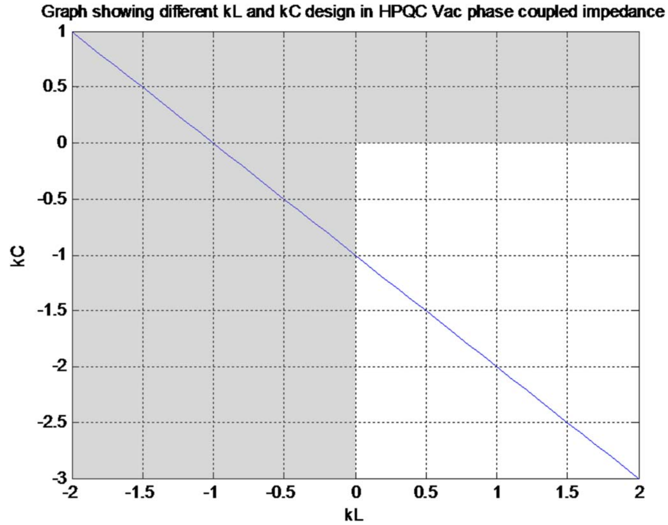

Fig. 6. Different possible combinations of Vac phase coupled inductance (k_L) and capacitance (k_C) ratio.

In HPQC, the Vac phase coupled impedance is formed by the coupled inductance L_a and capacitance C_a, whose equivalent impedance can be expressed as (12). It is further assumed in the expression that the impedance of coupled inductance X_{La} and coupled capacitance X_{Ca} are k_L and k_C times of the coupled impedance X_{LCa}, also shown in the following:

$$X_{\text{LCa}} = -(X_{La} + X_{Ca}) = -(k_L + k_C)X_{\text{LCa}}. \tag{12}$$

The relationship between the values of k_L and k_C can be then obtained from (12), as expressed in the following:

$$-k_L - k_C = 1. \tag{13}$$

The graph of k_C against k_L is plotted in Fig. 6 according to (13). It is worth noticing that the combinations in the shaded area are invalid since $k_L < 0$ or $k_C > 0$, which contradicts with the nature of inductor and capacitor impedance.

Theoretically, the value of Vac phase coupled inductance and capacitance can be chosen along the line in the unshaded area in Fig. 6. However, with harmonic compensation consideration, the effect of harmonic impedance on the operation voltage should be also included.

With reference to the expression in (13), the impedance at the hth harmonics can be expressed as

$$X_{\text{LCah}} = -(X_{\text{Lah}} + X_{\text{LCah}}) = -\left(hk_L + \frac{1}{h}k_C\right) X_{\text{LCa}}. \tag{14}$$

By substituting (13) into (14), the expression in (15) can be obtained, which is merely important for the analysis that follows, i.e.,

$$X_{\text{LCah}} = -\frac{1}{h}\left[(h^2 - 1)k_L - 1\right] X_{\text{LCa}}. \tag{15}$$

Recall from (9) that the harmonic compensation voltage V_{invaLCh} is not only dependent on the harmonic impedance

X_{LCah} but also on the load harmonic current I_{Lh}. Load current harmonics are usually expressed as a percentage of fundamental current. Assuming that the load harmonic current at the hth harmonic is r_h times of fundamental and considering the relationship between Vac phase compensation current I_{ca} and fundamental load current I_{L1}, the load harmonics can be then expressed as (16). For simplicity, the denominator is defined as A in the contents that follow. Thus,

$$\begin{aligned} I_{\mathrm{Lh}} &= r_h I_{L1} \\ &= r_h \left(\frac{I_{ca}}{\sqrt{\left(0.2887PF_L + \sin\left(\cos^{-1}(PF_L)\right)\right)^2 + (0.5PF_L)^2}} \right) \\ &= r_h \left(\frac{I_{ca}}{A} \right). \end{aligned} \tag{16}$$

Through substituting (11), (15), and (16) into (9), the expression for determining the harmonic compensation voltage for HPQC can be obtained, as shown in the following:

$$V_{\mathrm{invaLCh}}^2 = \sum_{h=2}^{\infty} V_{ac}^2 \cdot \frac{(r_h)^2}{A^2} \cdot (\sin\theta_{ca})^2 \cdot \left\{ \frac{1}{h} \left[(h^2-1)k_L - 1 \right] \right\}^2. \tag{17}$$

The value of k_L for minimum harmonic compensation voltage V_{invaLCh} can be then determined in a similar manner, by taking the derivative of (17) with k_L and setting it as zero, as shown in the following:

$$\frac{d\left(V_{\mathrm{invaLCh}}^2\right)}{dk_L} = \sum_{h=2}^{\infty} \left\{ V_{ac}^2 \cdot \frac{(r_h)^2}{A^2} \cdot (\sin\theta_{ca})^2 \cdot \left[\frac{\left(2(h^2-1)\right)^2}{h^2} k_L - \frac{2(h^2-1)}{h^2} \right] \right\} = 0. \tag{18}$$

The expression in (19) can be then obtained by further manipulations of (18), i.e.,

$$k_L = \frac{\sum_{h=2}^{\infty} (r_h)^2 \cdot \frac{2(h^2-1)}{h^2}}{\sum_{h=2}^{\infty} (r_h)^2 \cdot \frac{2(h^2-1)^2}{h^2}}. \tag{19}$$

Furthermore, in cophase traction power supply system, Vbc phase is unloaded. Ideally, no harmonic compensation is required from the Vbc phase converter. Therefore, the Vbc phase coupled impedance may be designed according to the minimum operation voltage V_{invaLC}, as expressed in

$$\begin{aligned} X_{\mathrm{LCb}} &= \frac{V_{bc}\sin\theta_{cb} + \sqrt{V_{\mathrm{invaLC}}^2 - V_{bc}^2\cos^2\theta_{cb}}}{I_{cb}} \\ &= \frac{V_{bc}\sin\theta_{cb} - \sqrt{V_{\mathrm{invaLC}}^2 - V_{bc}^2\cos^2\theta_{cb}}}{I_{cb}}. \end{aligned} \tag{20}$$

C. HPQC Operation Voltage With the Proposed Design

Assuming that the HPQC parameter is designed according to previous discussion for minimum operation voltage [refer to (11)], the HPQC operation voltage may be determined by substituting (8), (9), (11), and (17) into (7). The result is given in (21), shown at the bottom of the page.

As for the HPQC dc link operation voltage, it may be calculated as square root 2 times of the HPQC operation voltage, i.e., V_{invaLC}, as expressed in (22), shown at the bottom of the page.

D. Comprehensive HPQC Design Procedure

Based on previous discussions and analysis, the detailed procedure for the HPQC parameter design for minimum operation voltage under both fundamental and harmonic compensation is provided in the following.

1) Select the Vac phase coupled impedance according to (11).
2) Calculate the Vac phase coupled inductance L_a according to (23), which is obtained by substituting (11) and (19) into (12), i.e.,

$$L_a = -\frac{k_L X_{\mathrm{LCa}}}{\omega_1} = \frac{k_L \cdot V_{ac}\sin\theta_{ca}}{\omega_1 I_{ca}}. \tag{23}$$

3) Calculate the Vac phase coupled inductance according to (24), which is obtained through substituting (11) and (13), i.e.,

$$\begin{aligned} C_a &= \frac{1}{\omega_1 k_c X_{\mathrm{LCa}}} = \frac{1}{\omega_1(-1-k_L)X_{\mathrm{LCa}}} \\ &= -\frac{I_{ca}}{\omega_1(-1-k_L)V_{ac}\sin\theta_{ca}}. \end{aligned} \tag{24}$$

4) Calculate the Vbc phase coupled impedance according to (20) and

$$L_b = \frac{X_{Lb}}{\omega_1}. \tag{25}$$

5) Determine the dc link operation voltage in HPQC according to (22).

$$V_{\mathrm{invaLC}} = \sqrt{V_{ac}^2 \cdot (\cos\theta_{ca})^2 + \sum_{h=2}^{\infty} V_{ac}^2 \cdot \frac{(r_h)^2}{A^2} \cdot (\sin\theta_{ca})^2 \cdot \left\{ \frac{1}{h} \left[(h^2-1)k_L - 1 \right] \right\}^2} \tag{21}$$

$$V_{\mathrm{DC\_LC}} = \sqrt{2}V_{\mathrm{invaLC}} = \sqrt{2V_{ac}^2 \cdot (\cos\theta_{ca})^2 + 2\sum_{h=2}^{\infty} V_{ac}^2 \cdot \frac{(r_h)^2}{A^2} \cdot (\sin\theta_{ca})^2 \cdot \left\{ \frac{1}{h} \left[(h^2-1)k_L - 1 \right] \right\}^2} \tag{22}$$

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

IV. CASE STUDY AND SIMULATION

In order to verify the theory and analysis developed during the discussion for HPQC parameter design for minimum operation voltage in fundamental and harmonic compensation, a case study has been done. Shown in Table I is the practical on-site data of the harmonic distribution in traction load of the WuQing substation in China [26]. Traction load power factor usually ranges from 0.8 to 0.9, with an average of 0.85. The analysis that follows is performed based on these assumptions.

As introduced, the operation voltage for HPQC using the proposed parameter design may be determined by (21). In order to eliminate the effect of PCC voltage in the analysis, the operation voltage is expressed in per unit, with base of V_{ac}, as expressed in (26), shown at the bottom of the page. It can be observed from the expression that the HPQC operation voltage is dependent on load power factor, harmonics, and HPQC coupled impedance (both inductance and capacitance).

By substituting the data in Table I into (19), the value of k_L in the proposed design can be determined as 0.023. The corresponding HPQC operation voltage rating is calculated using (23), and the value is 0.4833. This value is close to the minimum HPQC operation for fundamental compensation, i.e., 0.48. The value corresponds to HPQC dc link voltage of around 18.7 kV for a 27.5-kV PCC voltage. Notice that, conventionally, the coupled inductance and capacitance parameter in a hybrid-structured compensator is tuned at the frequency where system harmonics are mostly concentrated. In the WuQing substation, this corresponds to the third harmonics, whose k_L value is around 0.125, and is actually not the point of minimum operation voltage. This shows that different from the conventional design, the HPQC operation voltage can be minimized under comprehensive compensation (including harmonics) using the proposed design procedure.

In order to do further verifications, simulations are done using PSCAD. The circuit schematics can be found in Fig. 2. The substation transformer is composed of two single-phase transformers with V/V connections. The parameters within the simulation are selected based on the existing practical traction power supply system. The three-phase power grid is around 110 kV, and the traction load is around 27.5 kV. The traction load is around 15 MVA, and the load power factor is around 0.85. The system source impedance is calculated as 2 mH according to the short-circuit capacity of common traction power supply of 750 MVA. The load harmonics are designed according to the data in Table I, whose higher peak load current condition is being selected.

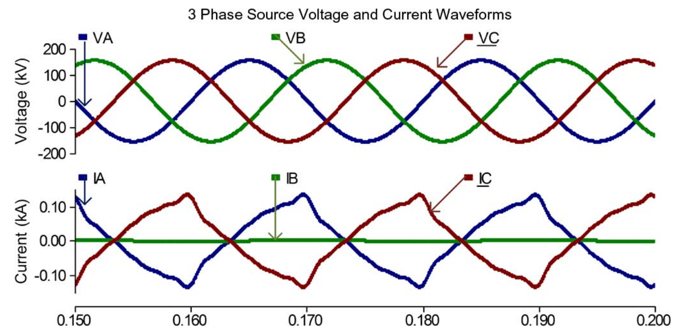

Fig. 7. Simulated three-phase source voltage and current waveforms obtained without power quality compensation.

TABLE II
HPQC PARAMETER SETTINGS IN THE TWO SIMULATED CONDITIONS

Condition	La	Ca	Lb
A. LC tuned at 3rd harmonics	19.7mH	57 uF	8 mH
B. Proposed Design	6.6 mH	62.2uF	8 mH

In the simulation, the system source current unbalance and harmonic distortions are being monitored, and the three-phase source power factor is calculated according to IEEE Standard 1459-2010 "Definitions for the Measurement of Electric Power Quantities Under Sinusoidal Nonsinusoidal, Balanced or Unbalanced Conditions." The system source voltage and current waveforms without power quality compensation are shown in Fig. 7. The system source current unbalance is 100%, with harmonic distortions of 14.7%, whereas the three-phase source power factor is only 0.6. Obviously, the system source power quality is far from satisfactory. Power quality compensation is thus required.

In order to provide comprehensive power quality compensation of system unbalance, reactive power, and harmonics, HPQC is connected across the two substation single-phase outputs and is switched in. Two conditions are being simulated, namely, HPQC Vac phase coupled LC values tuned at third harmonic frequency and HPQC Vac phase coupled LC values using the proposed design. The parameter setting is chosen according to the theory developed and is shown in Table II. Notice that the overall Vac phase fundamental coupled impedance is exactly the same, which offers the minimum HPQC operation voltage during fundamental compensation, in the two conditions. The only difference is the value of LC parameters. Details of the simulation results and analysis are shown in the following.

A. HPQC Vac Phase Coupled LC Values Tuned at Third Harmonic Frequency ($V_{\mathrm{DC}} = 18.7$ kV)

First of all, the parameter design for hybrid filter, being used in most research studies, is simulated. It has been suggested

$$k_{\mathrm{inv}} = \frac{V_{\mathrm{invaLC}}}{V_{ac}} = \sqrt{(\cos\theta_{ca})^2 + \sum_{h=2}^{\infty}\frac{(r_h)^2}{A^2}\cdot(\sin\theta_{ca})^2\cdot\left\{\frac{1}{h}\left[(h^2-1)k_L - 1\right]\right\}^2} \tag{26}$$

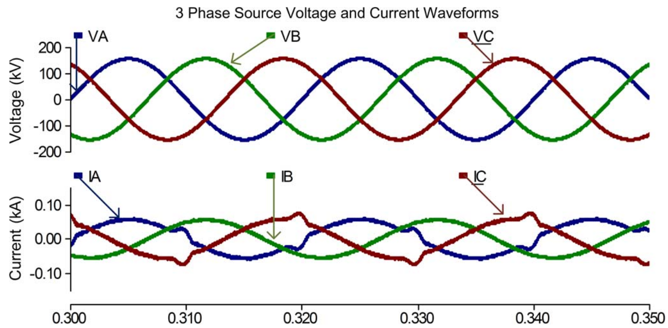

Fig. 8. Simulated three-phase source voltage and current waveforms obtained for cophase traction power supply system with HPQC of Vac phase coupled LC values tuned at the third harmonics.

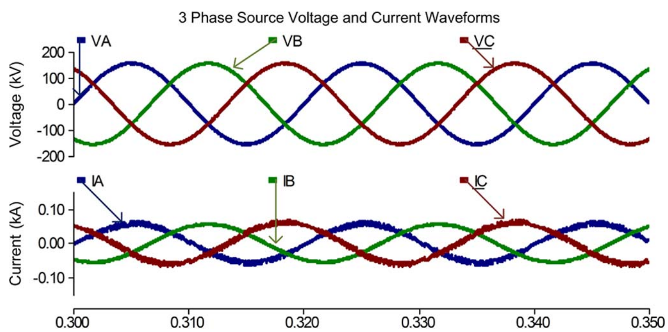

Fig. 9. Simulated three-phase source voltage and current waveforms obtained for cophase traction power supply system with HPQC of the proposed parameter design.

in various research studies that the inductance and capacitance values in the LC branch of hybrid filter can be tuned to the frequency where system harmonics are mostly concentrated to minimize the operation voltage. For instance, according to the data in Table I, the load harmonics are mostly concentrated at the third harmonics. Therefore, in this simulation subsection, the HPQC Vac phase coupled LC values are tuned to the third harmonics, and the parameters are shown in Table II.

The dc link voltage used is 18.7 kV, which can be concluded from (21), to show the pros of the proposed HPQC design. The simulated three-phase source voltage and current waveforms are shown in Fig. 8. It can be observed that the system source current unbalance and harmonics are not completely eliminated. The system source current harmonic distortion is 21%, whereas its unbalance is 8%. The harmonic compensation performance is thus not satisfactory.

B. HPQC Vac Phase Coupled LC Values Using the Proposed Design ($V_{\mathrm{DC}} = 18.7$ kV)

Next, the system performance of HPQC with the proposed parameter design under harmonic compensation is investigated. According to (21), the HPQC operation voltage rating is around 0.4833 using the proposed parameter design under the specified condition. This corresponds to a dc link voltage of around 18.7 kV for a 27.5-kV PCC voltage.

The simulated three-phase source voltage and current waveforms are shown in Fig. 9. It can be observed that the three-phase source current harmonics and unbalance are eliminated. Furthermore, the reactive power is also compensated. This can be verified by its harmonic distortions of 2.2%, unbalance of 4%, and power factor of 0.99.

A summarized system performance obtained from the simulations mentioned is shown in Table III. The dc link voltage used is 18.7 kV during compensation. It can observed from the data that, with the proposed HPQC parameter design, the HPQC operation voltage can be lowered and can also provide satisfactory compensation performance. With the same dc link voltage, the compensation performance is not satisfactory using parameter design normally used previously.

It is also found that, using the conventional design, the compensation performance is satisfactory only when the dc link operation voltage reaches 22 kV. There is, therefore, a 15% further reduction in operation voltage using the proposed HPQC design.

TABLE III
SUMMARIZED SIMULATED PERFORMANCES

Condition	Source Current THD	Source Current Unbalance	Source Power Factor
Without compensation	14.7%	99%	0.6
A. LC tuned at 3rd harmonics	21%	8%	0.9944
B. Proposed Design	2.2%	4%	0.9998

TABLE IV
SIMULATION RESULTS FOR HPQC COMPENSATION WITH THE PROPOSED PARAMETER DESIGN UNDER DIFFERENT LOAD POWER FACTORS

Load Power Factor	Before Compensation			After compensation using proposed HPQC parameter		
	THD	Unbalance	PF	THD	Unbalance	PF
0.1	14.7	100	0.0709	25.00	21.0	0.9721
0.2	14.7	100	0.1417	10.04	13.0	0.9849
0.3	14.7	100	0.2124	6.49	9.2	0.9933
0.4	14.7	100	0.2817	5.40	7.06	0.9960
0.5	14.7	100	0.3538	4.29	5.56	0.9975
0.6	14.7	100	0.4474	3.84	4.95	0.9981
0.7	14.7	100	0.5062	3.18	4.34	0.9983
0.8	14.7	100	0.5658	3.45	3.85	0.9987
0.9	14.7	100	0.6365	24.59	15.67	0.9817
1.0	14.7	100	0.7144	52.39	33.19	0.9345

C. HPQC Vac Phase Coupled LC Values Using the Proposed Design Under Different Load Power Factor Conditions ($V_{\mathrm{DC}} = 18.7$ kV)

In order to evaluate the power quality compensation ability of HPQC with the proposed design, simulations are done again under different load power factor conditions. Notice that critical conditions of totally load active or reactive power are also included to have comprehensive investigations. The results are shown in Table IV. It can be observed from the results that the designed HPQC can provide satisfactory power quality compensation for wide range of reactive power, except for conditions near loadings with totally reactive power or active power. This can be explained by parameter design exceeding designed range for heavy reactive power loading and insufficient dc link operation voltage for active power transfer under load with total active power. Since traction load power factor

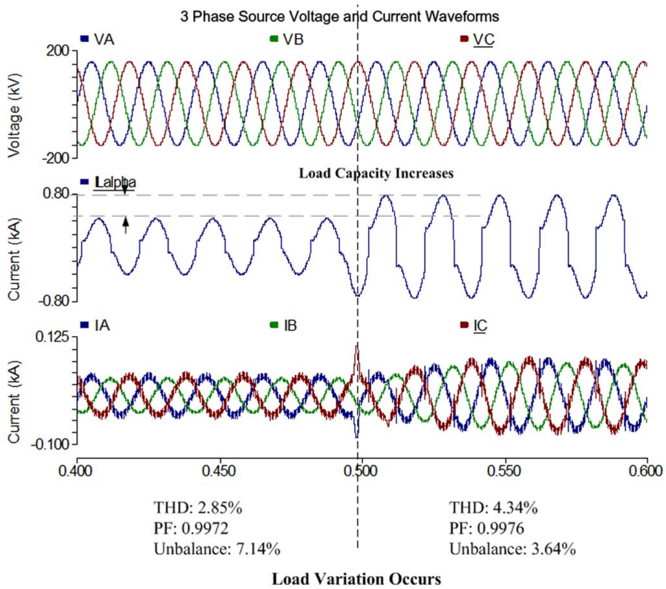

Fig. 10. Simulated three-phase source voltage and current waveforms obtained from cophase traction power supply system with HPQC of the proposed parameter design during load variations.

ranges from 0.8 to 0.85, the proposed parameter design for HPQC can provide satisfactory compensation for most loading conditions.

D. HPQC Vac Phase Coupled LC Values Using the Proposed Design Under Varying Load ($V_{\mathrm{DC}} = 18.7$ kV)

In order to further evaluate the system performance using the proposed design, simulations are done with a varying load. Suppose that the load capacity is increased from 0.6 to full rated load value near 0.5 s, the simulated primary source current and voltage waveforms are shown in Fig. 10.

It can be observed that the system performance is within standard using the proposed parameter design when loading condition is varied.

V. Experimental Verifications

In order to verify the system performances of the proposed cophase traction power supply system with HPQC of minimum operation voltage and its corresponding design under comprehensive compensation, including harmonic consideration, a low-capacity laboratory-scaled hardware prototype is constructed. It can be observed from (23) that the HPQC operation voltage is proportional to the PCC voltage V_{ac} and is independent of fundamental loading capacity. Therefore, the validity of the proposed HPQC in reducing operation voltage can be verified using this low-capacity hardware prototype. The circuit schematic and hardware appearance of the prototype are shown in Fig. 11.

The V/V transformer is composed of two 5-kVA single-phase transformers. The traction load is represented using a rectifier $R{-}L$ circuit, with a linear capacity of 150 VA. The load resistance and inductance are around 10 Ω and 30 mH, respectively. The control of the compensation is accomplished using DSP2812 according to the control block diagram shown

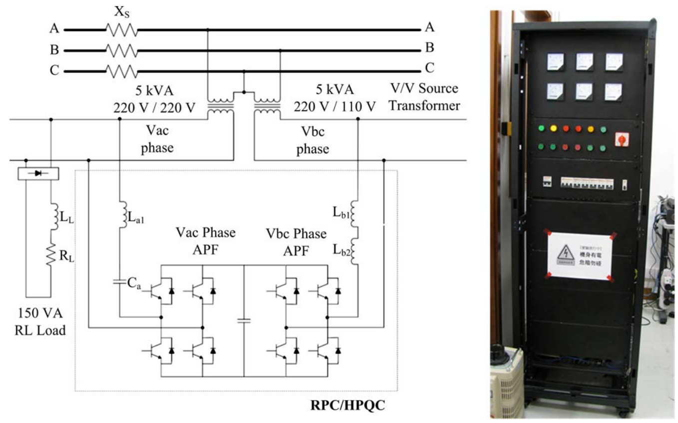

Fig. 11. Circuit schematic of the hardware prototype for verification of performances in the proposed cophase traction power supply system with HPQC.

TABLE V
HPQC Parameter Settings in Experimental Verifications

Condition	L_a	C_a	L_b
A. LC tuned at 3rd harmonics	4.7 mH	240 uF	8 mH
B. Proposed Design	2.00 mH	260 uF	8 mH

in Fig. 3. The PWM signal generation is achieved using hysteresis PWM tracking techniques. Details of the control may be found in [4] and [17].

The operation voltage of V_{ac} is 50 V. The presence of harmonics is caused by the nonlinear diode in the load rectifier and adds to the requirement of the HPQC operation voltage. According to the calculation in (6), the minimum dc link operation voltage for fundamental compensation is around 40 V. On the other hand, the dc link operation voltage is around 41 V using the proposed parameter design. In the experiment with compensation, two conditions are being verified. Similar to the simulation, the two conditions are HPQC with parameters LC tuned at 3rd harmonics (A) and Proposed Design (B). The detailed parameters are shown in Table V.

The system waveforms are captured using a Yokogawa DL750 16-channel ScopeCorder oscilloscope, and power quality is monitored using a Fluke43B single-phase power quality analyzer. Captured waveforms and screens are presented.

A. Cophase Traction Power Without Compensation

First, the system performance of cophase traction power without compensation is investigated. The system waveforms obtained are shown in Fig. 12. Absence of waveforms at Fig. 12(f)–(h) indicates absence of power quality conditioner. Waveform with larger amplitude refers to the voltage, whereas that with a smaller one refers to the current. It can be clearly observed that the system suffers from unbalance and harmonic problem. The system unbalance is around 99%, with current harmonic distortions of 17.8%.

B. Cophase Traction Power With HPQC Using the Conventional Design ($V_{\mathrm{DC}} = 41$ V)

Next, experimental results are done with cophase traction power supply with HPQC compensation using the conventional

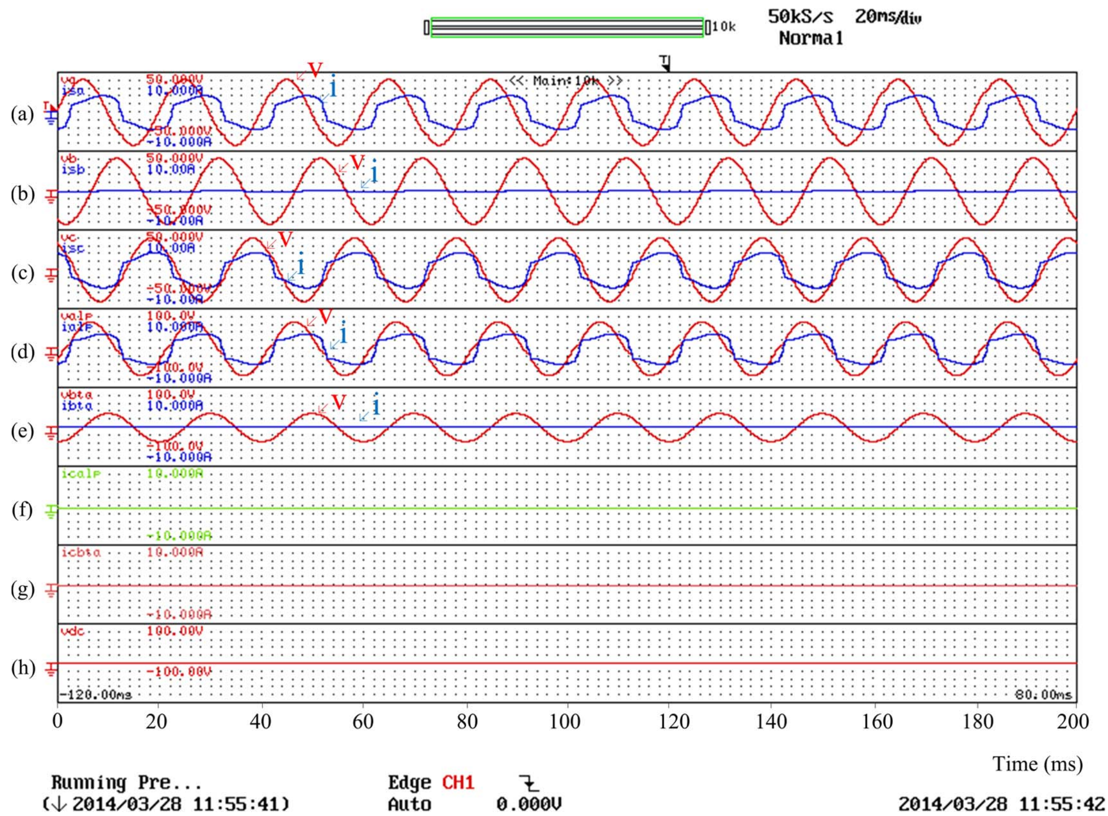

Fig. 12. Detailed experimental system waveforms captured for cophase traction power supply without compensation. (a) System source voltage and current of phase A. (b) System source voltage and current of phase B. (c) System source voltage and current of phase C. (d) Vac phase voltage and current at the secondary side. (e) Vbc phase voltage and current at the secondary side. (f) Vac phase compensation.

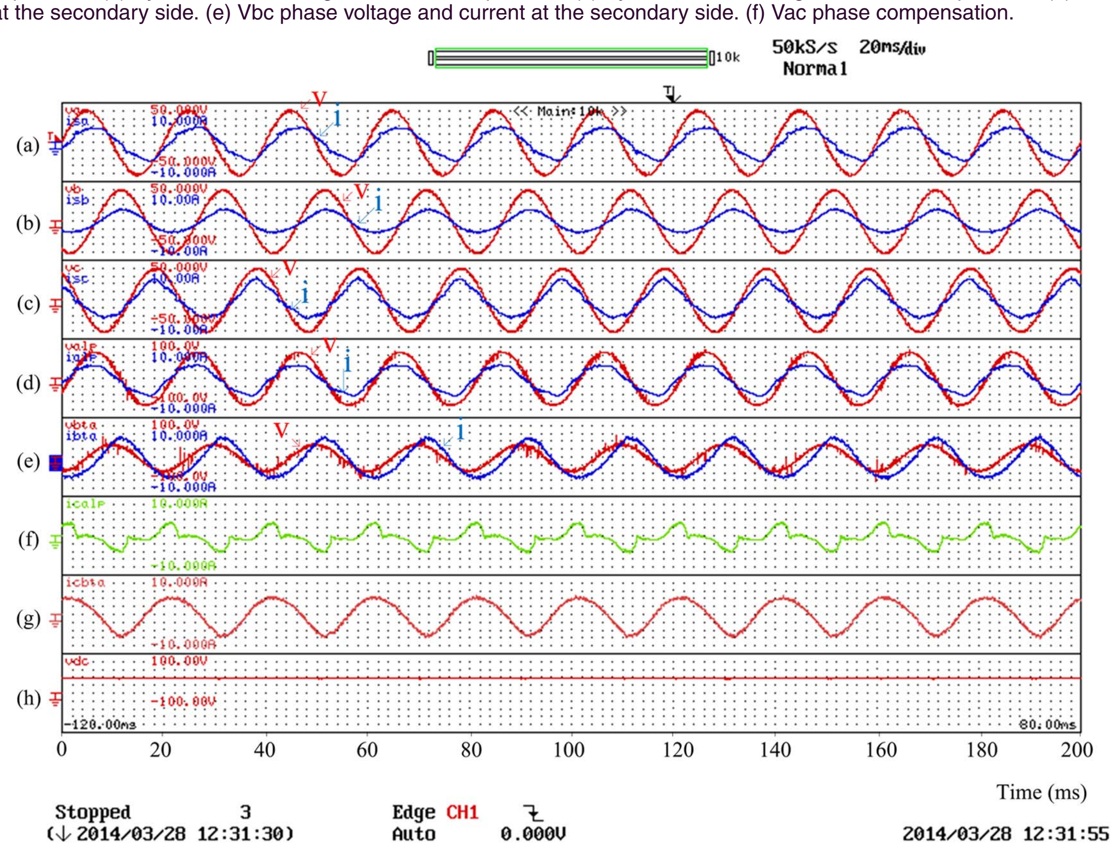

Fig. 13. Detailed experimental system waveforms captured for cophase traction power supply with the conventional HPQC design tuned at the third harmonics. (a) System source voltage and current of phase A. (b) System source voltage and current of phase B. (c) System source voltage and current of phase C. (d) Vac phase voltage and current at the secondary side. (e) Vbc phase voltage and current at the secondary side. (f) Vac phase compensation current. (g) Vbc phase compensation current. (h) DC link voltage.

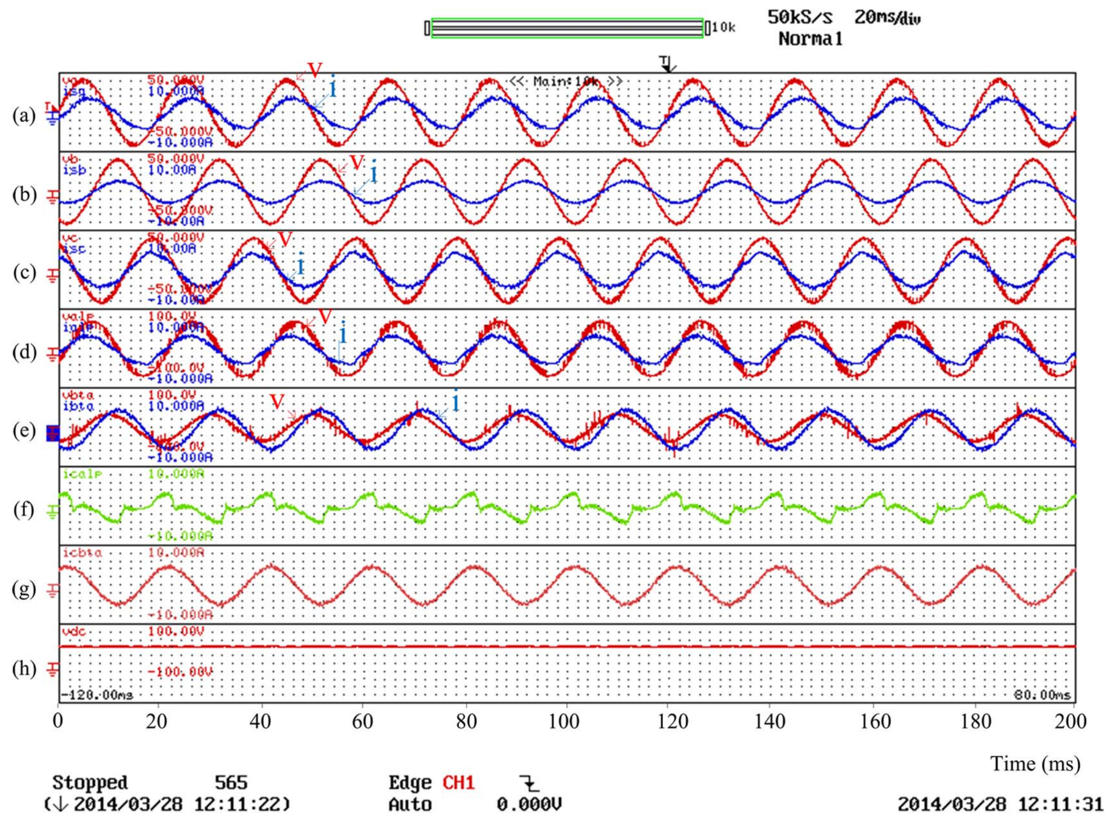

Fig. 14. Detailed experimental system waveforms captured for cophase traction power supply with the proposed HPQC design. (a) System source voltage and current of phase A. (b) System source voltage and current of phase B. (c) System source voltage and current of phase C. (d) Vac phase voltage and current at the secondary side. (e) Vbc phase voltage and current at the secondary side. (f) Vac phase compensation current. (g) Vbc phase compensation current. (h) DC link voltage.

parameter design. In other words, the Vac phase coupled inductance L_a and capacitance C_a is selected such that its resonant frequency is located at the third harmonics, where load harmonics are mostly concentrated (refer to Table I for reference). The HPQC circuit parameters are shown in Table III. In order to compare the performance with HPQC of the proposed design, the same dc link voltage of 41 V is being chosen. The system waveforms obtained through experimental results are shown in Fig. 13. It can be observed that, with the same dc link voltage, the three-phase source current waveforms suffer from obvious harmonic distortion, particularly at phase C current. This indicates that the compensation performance is not satisfactory when using HPQC of the conventional coupled impedance design. The system source current still suffers from significant harmonic problem.

C. Cophase Traction Power With Compensation With HPQC Using the Proposed Design ($V_{\mathrm{DC}} = 41$ V)

Next, experiments are conducted on the laboratory-scaled cophase traction power with HPQC using the proposed HPQC parameter design in this paper. The dc link voltage is also set as 41 V, according to the discussions and calculations. The HPQC circuit parameters can be found in Table III. The system waveforms obtained with RPC under such conditions are presented in Fig. 14. It can be observed that, compared with those in Fig. 13, the three-phase source current becomes balanced, and harmonics are eliminated. The total harmonic distortion is reduced to within 3%, while the system unbalance is also reduced.

TABLE VI
COMPARISONS OF SYSTEM COMPENSATION PERFORMANCE

Condition	Source Current THD	Source Current Unbalance	Source Power Factor
Without compensation	17.8%	99%	0.66
A. HPQC Compensation (LC tuned at 3rd harmonics)	10.3%	18%	0.96
B. HPQC Compensation (Proposed Design)	3.5%	14%	0.97

For comparisons, summarized data of system statistics without compensation and with HPQC compensation using the proposed and conventional parameter designs ($V_{dc} = 41$ V) are shown in Table VI. Recorded waveforms and power quality data for the three phases of the primary source grid are shown in Figs. 15–17. It can be observed from the figures that, before compensation, the three-phase power is unbalanced and is mostly concentrated at phase A and phase C. During power quality compensation, active power is transferred from the Vbc phase to the Vac phase. For performance using conventional HPQC design tuned at the third harmonics, the three-phase power is less balanced. On the other hand, for compensation

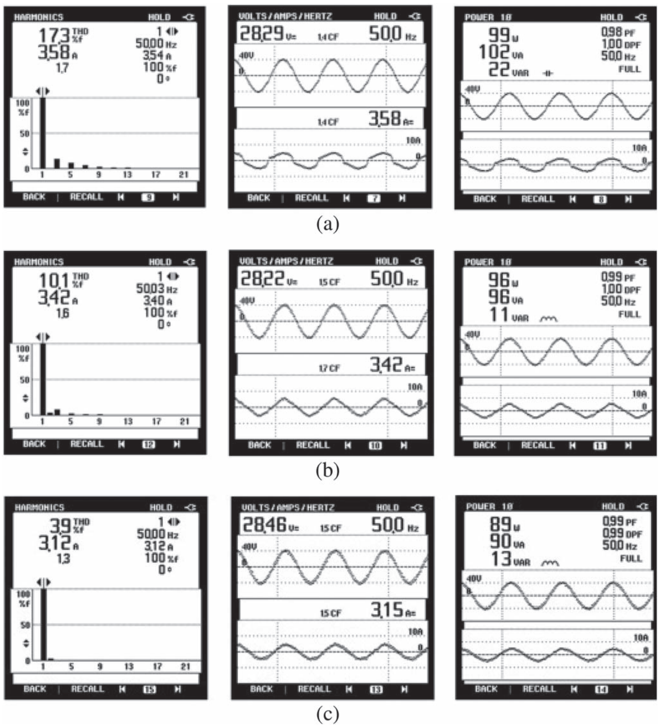

Fig. 15. Recorded experimental waveforms and power quality data from primary grid phase A. (a) Before compensation. (b) With HPQC compensation (LC tuned at third harmonics). (c) With HPQC compensation (proposed design).

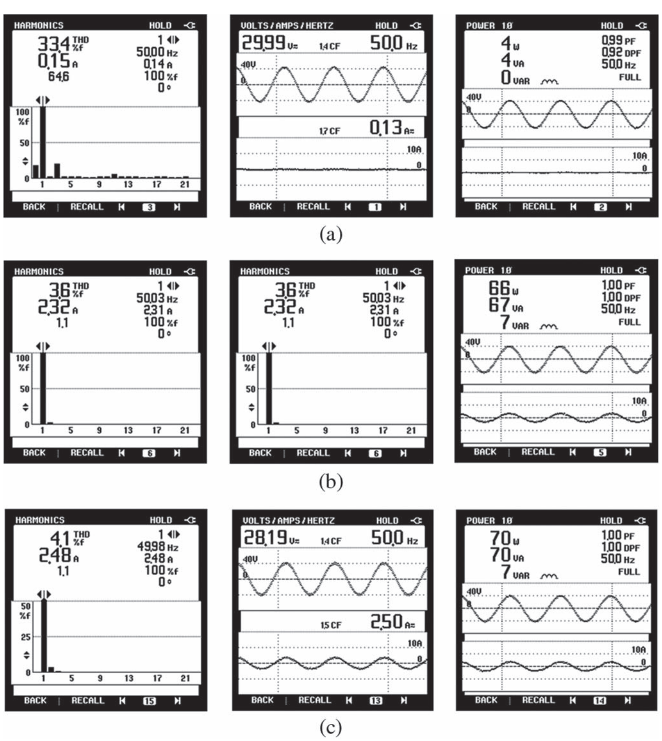

Fig. 16. Recorded experimental waveforms and power quality data from primary grid phase B. (a) Before compensation. (b) With HPQC compensation (LC tuned at third harmonics). (c) With HPQC compensation (proposed design).

using the proposed HPQC design, the three-phase power is more balanced. This shows that, with a low dc link voltage, the compensation performance using the proposed HPQC design is better than that using the conventional design. The data obtained are used to compute the parameters in Table VI according to the standard. It can be observed from the data that, with the conventional HPQC parameter design, the harmonic compensation performance is not satisfied at the investigated operation voltage. By contrast, using HPQC with the proposed parameter design, with the same operation voltage, the compensation performance is still satisfactory.

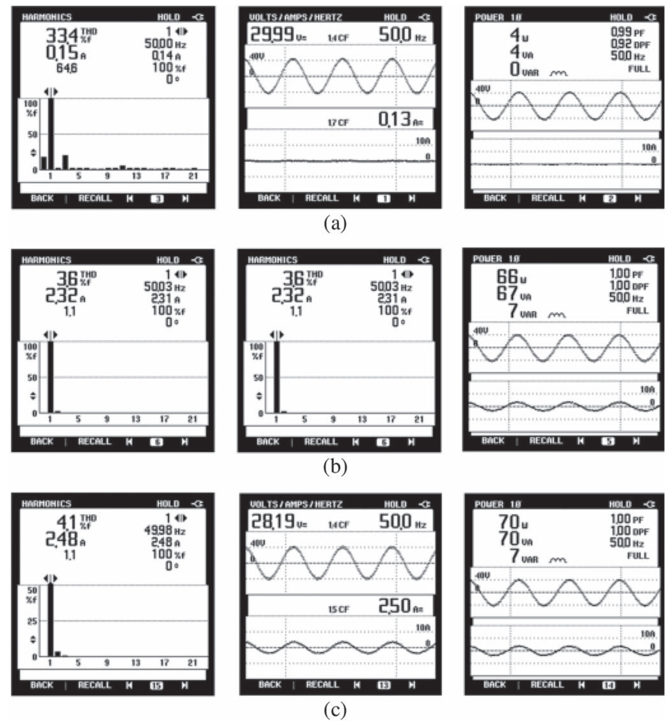

Fig. 17. Recorded experimental waveforms and power quality data from primary grid phase C. (a) Before compensation. (b) With HPQC compensation (LC tuned at third harmonics). (c) With HPQC compensation (proposed design).

D. Cophase Traction Power With Compensation With HPQC Under Load Variations

In order to further investigate the system performance during load variations using the proposed system design, the load is set to vary from 0.6 of rated ratings to full one. The experimental waveforms obtained are shown in Fig. 18. It can be observed from the waveforms that compensation can be provided for both load ratings. Details of the system power quality data obtained are shown in Table VII. It can be observed that the system power quality is within standard even when load varies. This shows that satisfactory compensation performance can be provided by HPQC using the proposed design when load varies.

The price of conventional STATCOM or RPC ranges from US \$38–\$50/kVA [26]; reduction of device capacity in HPQC thus also indicates cost reduction. Furthermore, the passive capacitor bank or SVC is relatively less expensive. According to the reference, the price of SVC is only around \$18/kVA. With nearly 45% reduction in HPQC operation voltage and thus device capacity, the price reduction is significant.

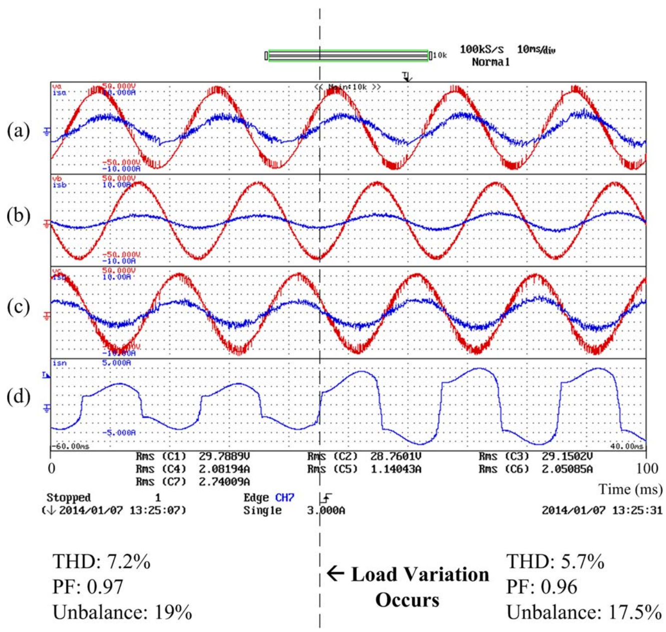

Fig. 18. Experimental system waveforms for cophase traction power supply with HPQC of the proposed parameter design under load variations, system voltage and current waveforms in (a) phase A, (b) phase B, (c) phase C, and (d) load current.

TABLE VII
COMPARISONS OF SYSTEM COMPENSATION PERFORMANCE FOR VARYING LOAD RATINGS

Condition	Source Current THD	Source Current Unbalance	Source Power Factor
Before Compensation: 0.6 of Full Load Ratings	18.1%	99%	0.70
After Compensation: 0.6 of Full Load Ratings	7.2%	19%	0.97
Before Compensation: 1.0 of Full Load Ratings	23.9%	99%	0.68
After Compensation: 1.0 of Full Load Ratings	5.7%	17.5%	0.96

VI. CONCLUSION

In this paper, the LC parameter design in HPQC has been investigated for reduction of the operation voltage under fundamental and harmonic compensation. HPQC is previously proposed for reduction in operation voltage when providing power quality compensation in cophase traction power. It works by introducing a capacitive LC branch as the coupled impedance. However, the design is mostly focused on fundamental compensation. Normally, the LC parameter is chosen at the frequency where load harmonic contents are mostly concentrated at for minimum compensator operation voltage, but the design lacks theoretical support. The HPQC design with minimum dc operation voltage for power quality compensation in cophase traction power supply system under the presence of load harmonics is being explored. The power quality compensation principle in cophase traction power supply is being reviewed, and HPQC is compared with conventional RPC to show the advantage of lower operation voltage and device ratings in HPQC. Based on the presence of load harmonics, the comprehensive design for HPQC is mathematically derived. It is shown that, under harmonic compensation, with a proper LC parameter design, a lower dc voltage operation can be achieved. This can eventually reduce the initial cost and switching loss. It is obtained through simulation and experimental verification that, with the proposed LC parameter design, there is a 15% further reduction in operation voltage compared with the conventional one, leading to a total of 43% reduction compared with the conventional RPC. Further study of the project includes proposing design so that HPQC can provide compensation for wider loading range.

ACKNOWLEDGMENT

The authors would like to thank the Macao Science and Technology Development Fund (FDCT) [Project number: 015/2008/A1], the University of Macau Research Committee [Project number: UL015/08-Y2/EEE/WMC01/FST, MYRG2014-00024-FST], and the University of Macau Power Electronics Laboratory for their support in this research work.

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