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# Robust Design of Hybrid Railway Power Conditioner for Efficient and Fast Railway System

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**ABSTRACT:** Co-phase 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.

**KEYWORDS:** Co-phase 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. Moreover, electrical isolations such as neutral sections between power regions are required, which causes reduction in locomotive speed. As a result, a traction power supply suitable for high-speed railway is required to overcome the aforementioned issues.

### II. EXISTING SYSTEM

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 existing, 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.

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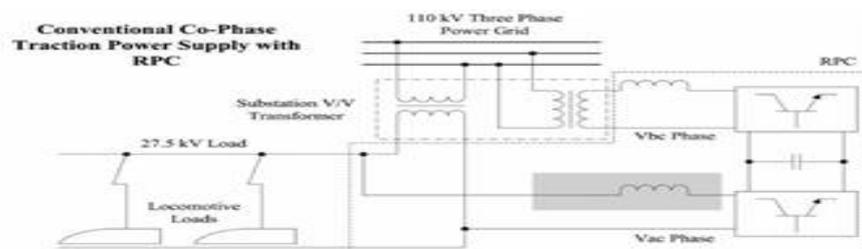


Fig. 1. Cophase traction power supply with the conventional RPC.

### III. PROPOSED SYSTEM

In this paper, the comprehensive HPQC design for minimum operation voltage under both fundamental and harmonic compensation is discussed. The control principle of comprehensive power quality compensation of system unbalance, reactive power, and harmonics in co-phase 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.

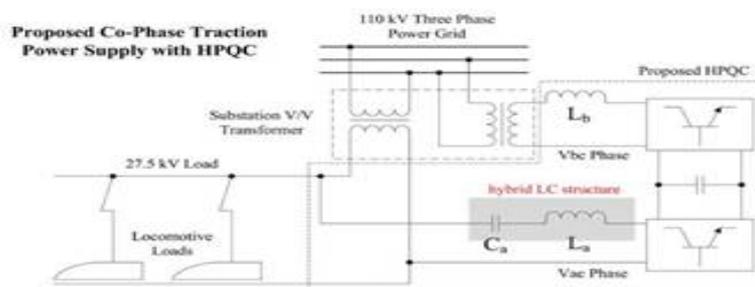


Fig. 2. Cophase traction power supply with the proposed HPQC.

At around 2012, in a hybrid device combining active and passive compensators, which is named as the hybrid power quality compensator (HPQC), was proposed for compensation in co-phase 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 co-phase traction power supply system. Hereafter, minimum dc operation voltage design of this HPQC under fundamental compensation of system unbalance and reactive power was discussed. However, 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. However, the idea still lacks theoretical support or mathematical derivation. The required output compensation power from a co-phase traction power quality compensator is shown in the following.

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

#### COMPARISONS BETWEEN COPHASE TRACTION WITH CONVENTIONAL AND PRAPOSED HPQC

First of all the compensation theory is briefly introduced. The system configurations of a typical cop-phase traction power with the conventional RPC and the proposed HPQC are shown in figures1 and 2 respectively. The power quality compensator is connected across the transformer.





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### 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. 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

$$V_{invaLC} = \sqrt{V_{invaLC1}^2 + V_{invaLCh}^2}$$

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

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

#### I. HPQC Design of minimum operation voltage for fundamental compensation

Fundamental compensation in co-phase 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 derivative of with  $X_{LCa}$  and setting it has zero. The process and result are consistent with the expression Notice that the negative sign in the expression refer to a capacitive coupled impedance. Thus

$$\frac{d(V_{invaLC1}^2)}{d(X_{LCa})} = V_{ac}|I_{caq1}| + X_{LCa} (|I_{caq1}|^2 + |I_{caq1}|^2)$$

$$= 0$$

$$X_{LCa} = -\frac{V_{ac} \sin \theta_{ca}}{I_{ca}}$$

#### II. 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 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 is the discussion of the HPQC design is presented based on the criteria of minimum fundamental operation voltage  $V_{invaLC1}$ . In other words, the parameter design for minimum operation voltage during harmonic compensation developed here does not alter the fundamental coupled impedance  $X_{LCa}$ .

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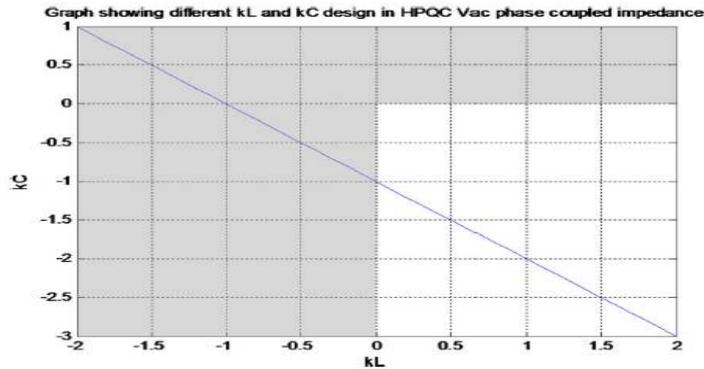


Fig. 6. Different possible combinations of Vac phase coupled inductance ( $k_L$ ) and capacitance ( $k_C$ ) ratio.

The expression for the impedance of coupled inductance and coupled capacitance

$$X_{LCa} = -(X_{La} + X_{Ca}) = -(k_L + k_C)X_{LCa}.$$

The relationship between the values of  $k_L$  and  $k_C$  can be expressed in the following:

$$-k_L - k_C = 1.$$

The impedance at the  $h$ th harmonics can be expressed as

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

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

The load harmonic current can be expressed as

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

The expression for determining the harmonic compensation voltage for HPQC can be obtained, as shown in the following:



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

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

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

The Vbc phase coupled impedance may be designed according to the minimum operation voltage  $V_{\text{invaLC}}$ , as expressed in

$$X_{\text{LCb}} = \frac{V_{bc} \sin \theta_{cb} + \sqrt{V_{\text{invaLC}}^2 - V_{bc}^2 \cos^2 \theta_{cb}}}{I_{cb}}$$

$$= \frac{V_{bc} \sin \theta_{cb} - \sqrt{V_{\text{invaLC}}^2 - V_{bc}^2 \cos^2 \theta_{cb}}}{I_{cb}}$$

### IV. HPQC OPERATION VOLTAGE WITH THE PROPOSED DESIGN

Assuming that the HPQC parameter is designed according to previous discussion for minimum operation voltage. As for the HPQC dc link operation voltage, it may be calculated as square root 2 times of the HPQC operation voltage.

#### IV. Comprehensive HPQC Design Procedure

The Vac phase coupled impedance  $L_{a is}$

$$L_a = -\frac{k_L X_{\text{LCa}}}{\omega_1} = \frac{k_L \cdot V_{ac} \sin \theta_{ca}}{\omega_1 I_{ca}}$$

Vac phase coupled inductance

$$C_a = \frac{1}{\omega_1 k_c X_{\text{LCa}}} = \frac{1}{\omega_1 (-1 - k_L) X_{\text{LCa}}}$$

$$= -\frac{I_{ca}}{\omega_1 (-1 - k_L) V_{ac} \sin \theta_{ca}}$$

Vbc phase coupled impedance

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$$L_b = \frac{X_{Lb}}{\omega_1}$$

The dc link operation voltage in HPQC

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

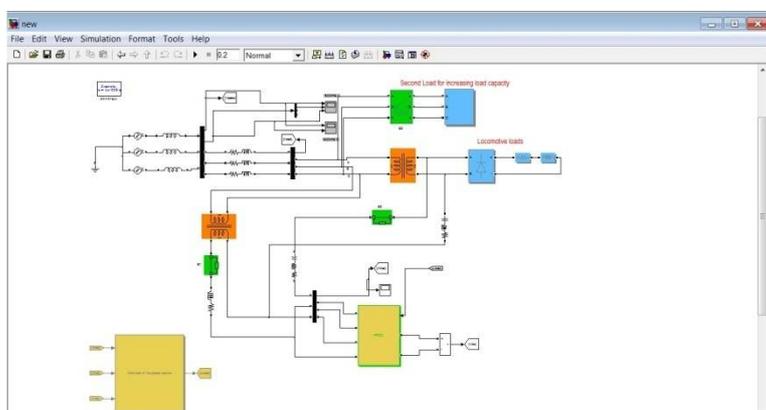
$$V_{\text{DC\_LC}} = \sqrt{2}V_{\text{invaLC}} = \sqrt{2V_{ac}^2 \cdot (\cos \theta_{ca})^2 + 2 \sum_{h=2}^{\infty} V_{ac}^2 \cdot \frac{(r_h)^2}{A^2} \cdot (\sin \theta_{ca})^2 \cdot \left\{ \frac{1}{h} [(h^2 - 1)k_L - 1] \right\}^2}$$

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

## V. CASE STUDY AND SIMULATION

### Simulation Circuit



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. Traction load

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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. 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 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 the value of  $k_L$  in the proposed design can be determined as 0.023. The corresponding HPQC operation voltage rating is calculated using 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 Figure 2. The substation transformer is composed of two single-phase trans-formers 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. 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 Non-sinusoidal, Balanced or Un-balanced Conditions.” The system source voltage and current waveforms without power quality compensation are shown in Figure 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.

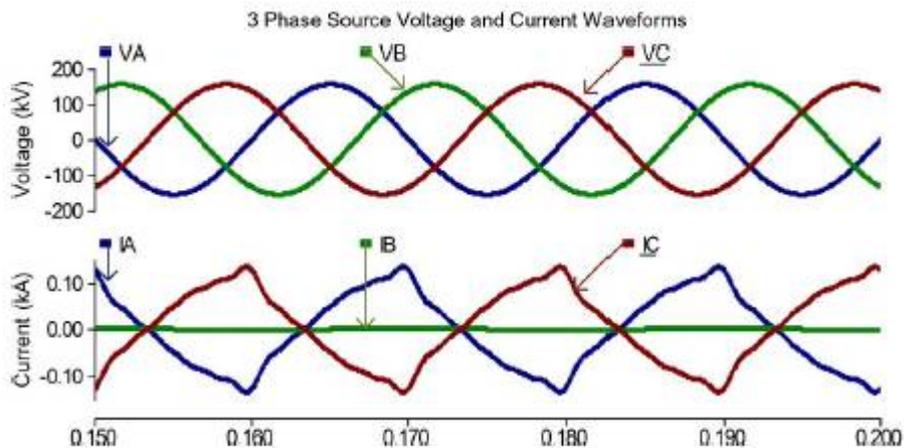


Fig. 7. Simulated three-phase source voltage and current waveforms obtained without power quality compensation.

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

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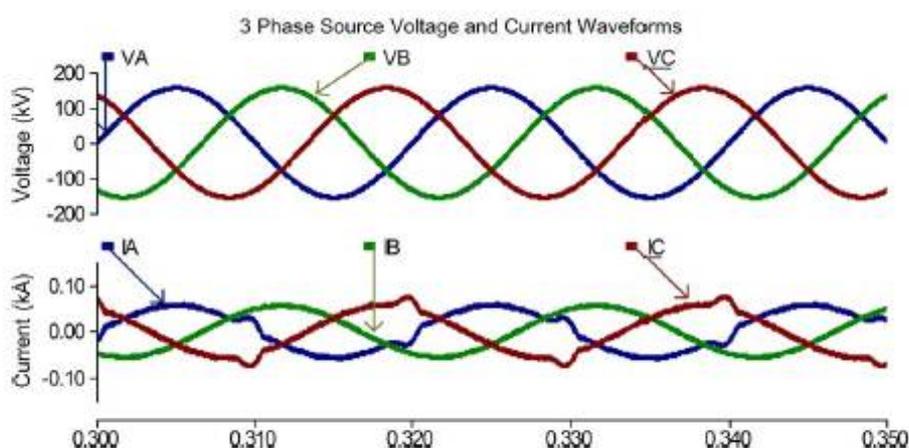
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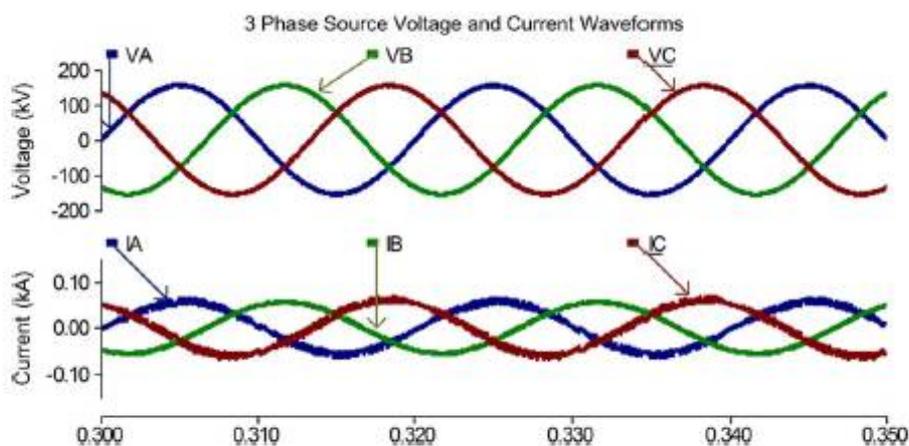
In order to provide comprehensive power quality compensation of system unbalance, reactive power, and harmonics, HPQC is connected across the two substation single-phase outputs and is switched in. Two conditions are being simulated, namely, HPQC Vac phase coupled  $LC$  values tuned at third harmonic 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 ( $V_{DC} = 18.7$ kV)

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



**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,

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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 wave-forms are shown in Figure 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 ( $V_{DC} = 18.7$ 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 wave-forms are shown in Figure 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 be 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.

## C. HPQC Vac Phase Coupled LC Values Using the Proposed Design under Different Load Power Factor Conditions ( $V_{DC} = 18.7$ 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 ranges from 0.8 to 0.85, the proposed parameter design for HPQC can provide satisfactory compensation for most loading conditions.

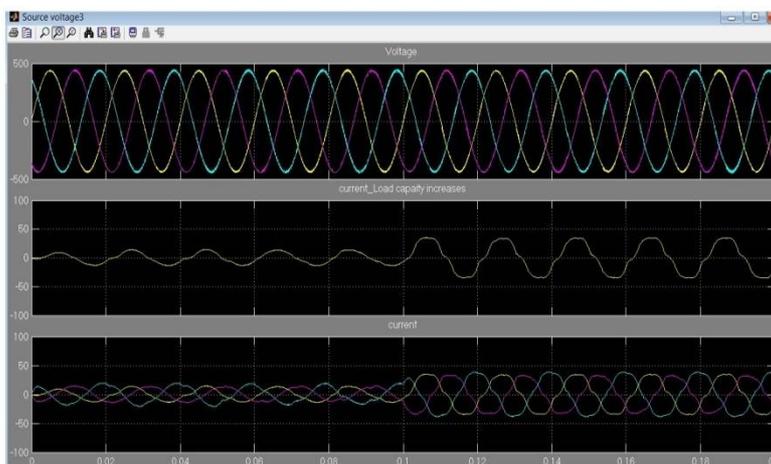


Fig. 10. Simulated three-phase source voltage and current waveforms obtained from co-phase traction power supply system with HPQC of the proposed parameter design during load variations.

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## D. HPQC Vac Phase Coupled LC Values Using the Proposed Design under Varying Load ( $V_{DC} = 18.7$ 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 Figure 10.

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

### EXPERIMENTAL VERIFICATIONS

In order to verify the system performances of the proposed co-phase 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 Figure 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  $10 \Omega$  and 30 mH, respectively. The control of the compensation is accomplished using DSP2812 according to the control block diagram shown in Figure 3. The PWM signal generation is achieved using hysteresis PWM tracking techniques.

TABLE V  
HPQC PARAMETER SETTINGS IN EXPERIMENTAL VERIFICATIONS

Condition	$L_a$	$C_a$	$L_b$
A. LC tuned at 3 <sup>rd</sup> harmonics	4.7 mH	240 $\mu$ F	8 mH
B. Proposed Design	2.00 mH	260 $\mu$ F	8 mH

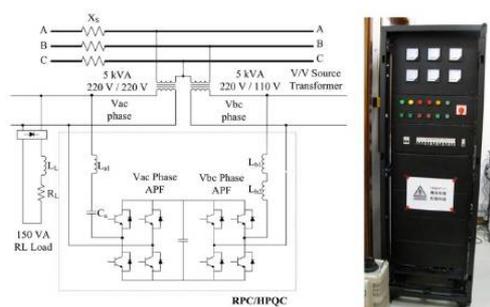


Figure 11. Circuit schematic of the hardware prototype for verification of performances in the proposed co-phase traction power supply system with HPQC.

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 3<sup>rd</sup> 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 Scope order oscilloscope, and power quality is monitored using a Fluke43B single-phase power quality analyzer. Captured waveforms and screens are presented.

### A. Co-phase Traction Power without Compensation

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First, the system performance of co-phase traction power without compensation is investigated. The system waveforms obtained are shown in Figure 12. Absence of waveforms at Figure 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. Co-phase Traction Power with HPQC Using the Conventional Design ( $V_{DC} = 41\text{ V}$ )

Next experimental results are done with co-phase traction power supply with HPQC compensation using the conventional 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 pro-posed design the same dc link voltage of 41 V is being chosen. The system waveforms obtained through experimental results are shown in Figure 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.

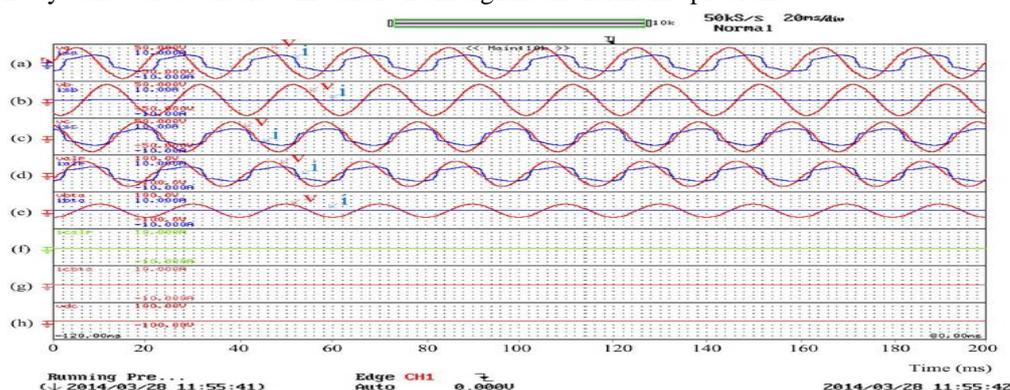


Figure 12. Detailed experimental system waveforms captured for co-phase traction power supply without compensation. (a) System source voltage and current of phase A. (b) System source voltage and current of phase B. (c) System source voltage and current of phase C. (d) Vac phase voltage and current at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

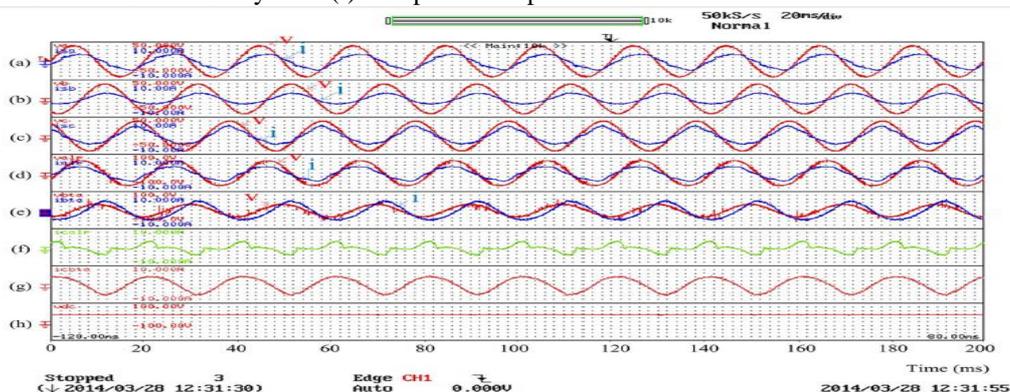


Figure 13. Detailed experimental system waveforms captured for co-phase traction power supply with the conventional HPQC design tuned at the third harmonics. (a) System source voltage and current of phase A. (b) System source voltage and current of phase B. (c) System source voltage and current of phase 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.

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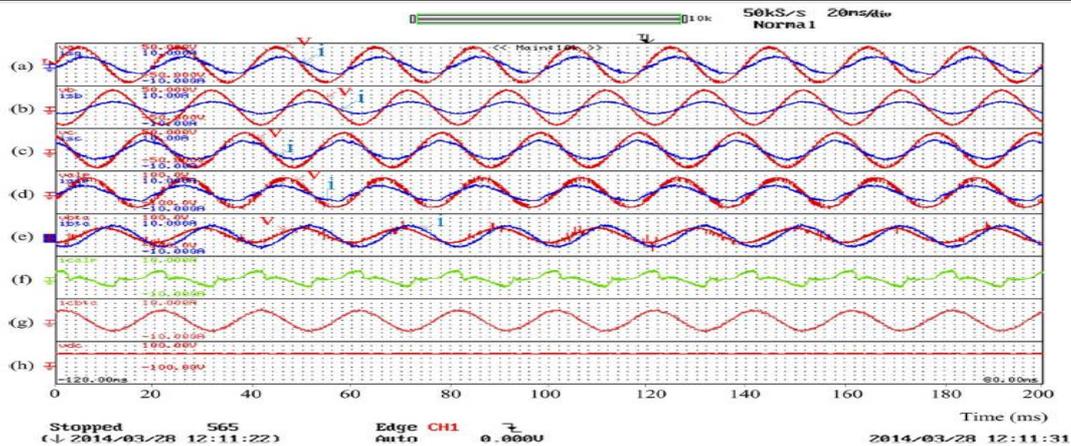


Fig. 14. Detailed experimental system waveforms captured for co-phase traction power supply with the proposed HPQC design. (a) System source voltage and current of phase A. (b) System source voltage and current of phase B. (c) System source voltage and current of phase C. (d) Vac phase voltage and current 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.

### C. Co-phase Traction Power with Compensation with HPQC Using the Proposed Design ( $V_{DC} = 41$ V)

Next, experiments are conducted on the laboratory-scaled co-phase 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 Figure 14. It can be observed that, compared with those in Figure 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 3 <sup>rd</sup> harmonics)	10.3%	18%	0.96
B. HPQC Compensation (Proposed Design)	3.5%	14%	0.97

For comparisons, summarized data of system statistics with-out 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 Figure 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 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.

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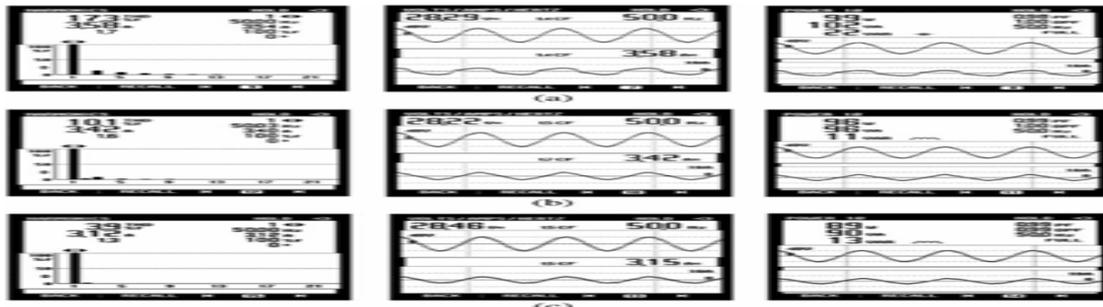


Fig. 15. Recorded experimental waveforms and power quality data from primary grid phase A. (a) before compensation. (b) With HPQC compensation ( $LC$  tuned at third harmonics). (c) With HPQC compensation (proposed design).

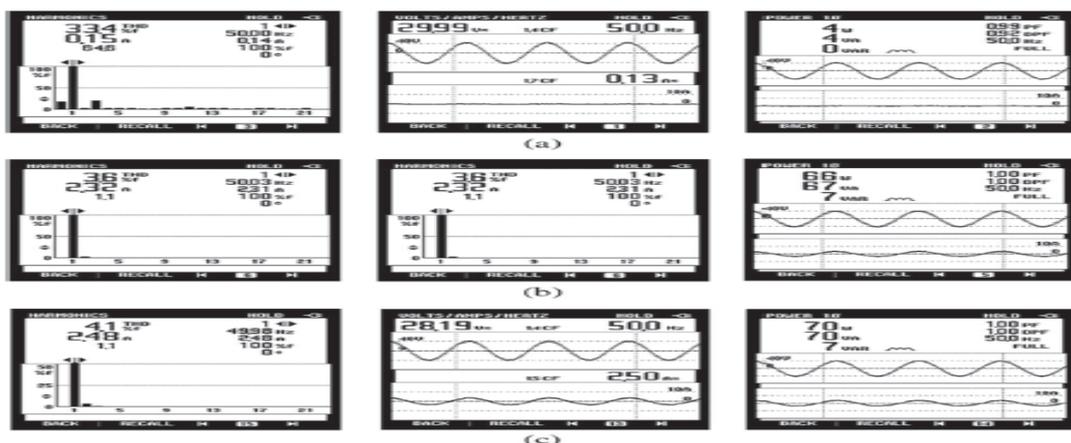
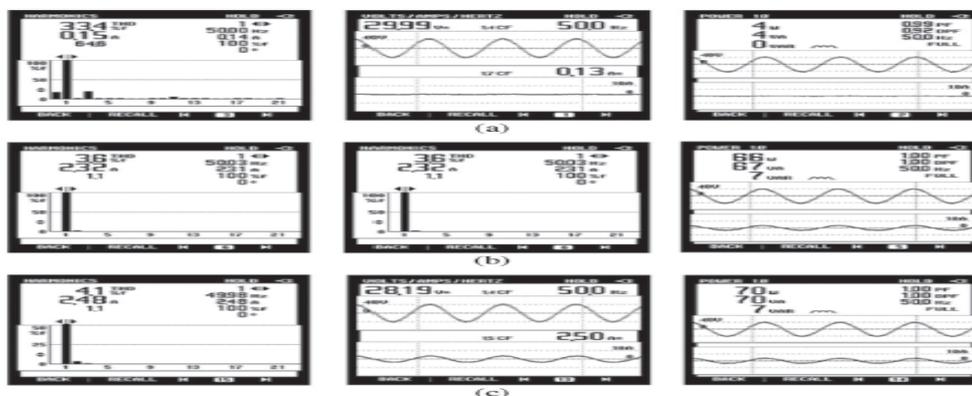


Fig. 16. Recorded experimental waveforms and power quality data from primary grid phase B. (a) before compensation. (b) With HPQC compensation ( $LC$  tuned at third harmonics). (c) With HPQC compensation (proposed design).



## D. Co-phase 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 Figure 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

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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.

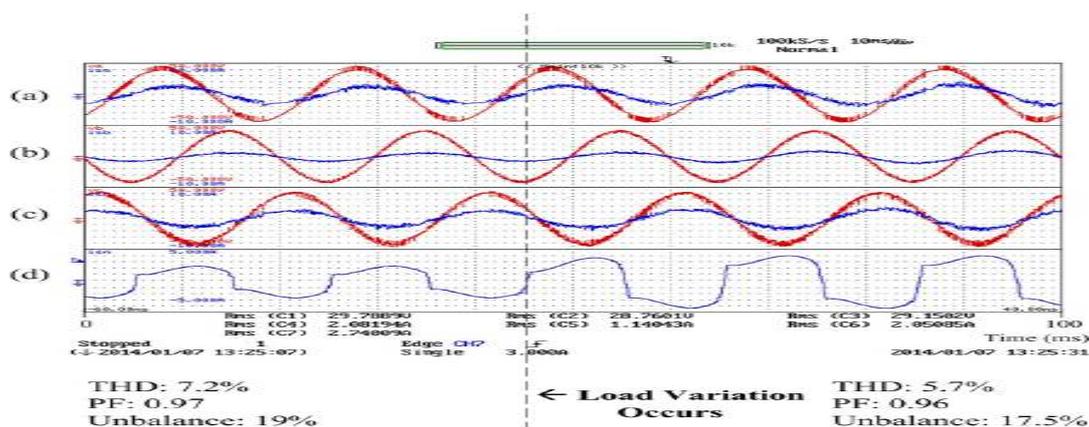


Fig. 18. Experimental system waveforms for co-phase traction power supply with HPQC of the proposed parameter design under load variations, system voltage and current waveforms in (a) phase A, (b) phase B, (c) phase C, and (d) load current

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 pro-posed for reduction in operation voltage when providing power quality compensation in co-phase 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 co-phase traction power supply system under the presence of load harmonics is being explored. The power quality compensation principle in co-phase 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.



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Further study of the project includes proposing design so that HPQC can provide compensation for wider loading range.

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